SCHOOL OF
CIVIL ENGINEERING

INDIANA
DEPARTMENT OF TRANSPORTATION

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-90/12

Final Report

EVALUATION OF COST-EFFECTIVENESS OF PAVEMENT SURFACE MAINTENANCE ACTIVITIES

Ibrahim M. Mouaket
Abdullah Al-Mansour
Kumares C. Sinha

PURDUE UNIVERSITY

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TO:	V.P. Drnevich, Director Joint Highway Research Project	August 22, 1990 Revised October 30, 1991 Project No. C-36-63M
FROM:	Kumares C. Sinha, Research Engineer Joint Highway Research Project	File No: 9-7-13
SUBJ:	Evaluation of Cost-Effectiveness of Pavement Surface Maintenance Activities	

Attached is the Final Report on the HPR Part II Study entitled, "Evaluation of Cost-Effectiveness of Pavement Surface Maintenance Activities". This report presents the results of the study including recommendations for implementation. This report was prepared and the research work was conducted by Messrs. I.M. Mouaket and A. Al-Mansour under my direction.

The report is forwarded for review, comment and acceptance by the INDOT and FHWA as fulfillment of the objectives of the research.

Respectfully submitted,

K C Sinha

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Final Report

EVALUATION OF COST-EFFECTIVENESS OF PAVEMENT SURFACE MAINTENANCE ACTIVITIES

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16. Abstract

This study covers pavement surface maintenance on three surface types: rigid, flexible and composite (asphalt overlay on rigid pavement). It addresses 3 main issues as follows: 1) Do routine maintenance activities make a difference in terms of pavement serviceability? If yes, how much? 2) Are chip and sand seal coating cost-effective? What is their optimal timing? 3) What management criteria should be used as a guide to make seal coating decisions on specific roadways? In resolving Issue #1, a stratified 2-stage sample of observational data was used in a statistical before/after comparison. SAS-General Linear Model was used due to its flexibility in treating continuous and class variables. Most activities showed significant effect (either alone or in combination with others) on Pavement Serviceability Ratings or Roughness Numbers. In resolving Issue #2, Life Cycle Cost Analysis was applied using agency and user costs. Results showed that optimal timing for seal coating is in the PSI range of 3.0 to 2.7, dependent on AADT. In resolving Issue #3, a literature search, telephone interviews and expert opinion survey were used to augment the findings on Issue #2 in generating a decision tree. The developed tree uses the available data at INDOT, although surface distress related criteria would be superior. The tree helps analyze the likely cause of distress, the preferred solution and a priority ranking in the case of funding shortages. Specific guidelines on the use of chip and sand seals are also provided.

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CHAPTER 1

INTRODUCTION

The process of wear in pavements starts when construction ends. Changes in temperature, moisture content or traffic, or small movements in the underlying or adjacent earth, creates stresses within the pavement structure. Such stresses are constantly working in all pavements to produce minor defects that are quite often unnoticeable. If these minor defects are not soon repaired, they can, and often do, develop into serious defects. Hence cracks, holes, depressions and other types of distress are the end result and visible evidence of pavement wear -- not the beginning.

There are different types of pavements: one type is made of a granular layer and an asphalt concrete surface or full depth asphaltic concrete (known as flexible); a second is made of a portland cement concrete slab placed directly on top of the subgrade or a granular layer (known as rigid); and finally, either a rigid pavement is overlaid with a layer of asphaltic concrete or a flexible pavement overlaid with a layer of portland cement concrete (known as composite), where the former is more popular than the latter. Each of the above mentioned types has its own unique characteristics, failures (distresses) and repair techniques.

1.1 Rigid Pavement Maintenance

In rigid pavements, the loads are distributed to the base and subgrade through bending stresses in the slab created by the load. There are three types of concrete slabs that are mostly used in Indiana. The three types are: jointed plain concrete, jointed reinforced concrete and continuously reinforced concrete.

Over 20 types of distresses have been observed to occur on rigid pavements, particularly as related to the most frequently used type -- the jointed reinforced concrete. These distresses have been grouped in different ways by different agencies. Some base their classification on the possible causes of distress [Army 1982]; others, on the nature of the failure [Mildenhall and Northscott 1986]; and some others, on combination of nature, consequence and possible cause of the distress [RTAC 1977].

Three major groupings are identified, each includes a number of distresses. These groupings are: joint defects, surface defects, and structural defects. Joint defects include: defective joint sealants, shallow spalling of joint arris or edge of slab, deep spalling, and cracks at joints. Surface defects include: inadequate skid resistance, surface irregularities, surface scaling, plastic shrinkage cracking and surface deterioration (popouts). Structural (internal) defects include: transverse cracks, longitudinal cracks, corner cracks, diagonal cracks, cracks around manholes and gullies, vertical slab movement, compression failures, and disintegration.

Repair techniques include resealing of joints and cracks, sawing grooves and re-doing of seals, thin bonded repairs, stitched pavement repairs, partial or full depth patching, grooving, adding a surface dressing of thin layer of mortar, mechanical roughening, grinding and milling, sealing with low viscosity resin or latex emulsion, thin overlays, and slab replacement.

The choice of the appropriate repair technique naturally depends on the type of distress, its cause, urgency of the situation, availability of funds and crews and whether other major work has been scheduled in the short run.

1.2 Flexible Pavement Maintenance

In contrast to rigid pavement, the load carrying capacity of flexible pavements is brought about by load-distributing of the layered system. Flexible pavements consist of a series of layers, with the highest quality material at or near the surface. Hence, the strength of a flexible pavement is a result of building up thick layers thereby distributing the load over the subgrade, rather than by the bending action of the slab [Yoder and Witczak 1974].

Again some 20 types of distresses have been observed on flexible pavements. These distresses have been grouped in different ways by different agencies. Some base their classification on the possible causes of distress [Army 1982]; others on the nature of failure [Asphalt Institute 1983]; and some others on the nature of the failure, its consequence and possible cause [RTAC 1977].

Four major grouping are identified in this study, each includes a number of distresses. These groupings are cracking, distortion, disintegration and skid hazards. Cracking includes; alligator cracks; edge cracks, edge joint cracks, lane joint cracks, reflection cracks, shrinkage cracks, slippage cracks, and widening cracks. Distortion includes: ruts; corrugations and shoving; grade depressions; upheaval; and utility cut depressions. Disintegration includes: potholes, and raveling. Skid hazard includes: bleeding or flushing asphalt; polished aggregate; loss of cover aggregate; longitudinal streaking; and transverse streaking.

Repair techniques include: crack filling; shallow patches; deep patching; aggregate seal coat patch; hot plant mix patching; asphalt emulsion slurry application; thin asphalt plant mix overlays; chip and seal coating; hot sand or hot slag screenings or hot rock screening application; rejuvenator spraying; planing and sealing. The choice of the appropriate repair technique depends on the same factors for rigid pavement.

1.3 Composite Pavement Maintenance

The asphalt overlay topping the PCC slab is aimed at: sealing the cracks of the rigid slabs underneath in order to protect the infrastructure from further and more severe deterioration; restoring the rideability on the deteriorated concrete pavement; improving skid resistance; and/or strengthening the pavement's structural (carrying) capacity. Like any other surface, the overlay wears from use and weather fluctuation, moisture and freeze/thaw cycles.

The asphalt layer in this case performs quite differently from that of flexible pavement. For one reason, the support underneath it is rigid and, as such, a number of subgrade-related distresses in flexible pavements are not observed here; another reason is that reflection cracking on this type of pavement is more frequent and extensive than on flexible pavements, particularly where the underlying base is a jointed reinforced concrete; a third reason is that the applied layer of asphalt depends on the strength of its bond with the rigid pavement for stability. If this bond is weakened, the asphalt tends to peal off -- a problem not observed in flexible pavements. In general, the behavior of composite pavements is more complex to understand and explain than flexible pavements.

Many major references combine flexible and composite pavement distresses together [Army 1982, RTAC 1977]. The distresses related only to composite pavements can be grouped under three sub-groups [Majidzadeh and Luther 1980]; these are: surface defects, pavement support, and cracking and joint related. Surface defects include: raveling, flushing or bleeding, patching and utility cut patching, disintegration or debonding, rutting, corrugations (washboarding).

Pavement support defects include: pumping, shattered slabs and settlement. Cracking and joint related defects include: transverse cracking, crack seal deficiency, pressure damage (upheaval), and longitudinal cracking.

Repair techniques include: surface treatments, rejuvenator application, aggregate seal coats, partial depth repairs, crack sealing, full depth repairs, thin overlays, skin patch, heat planing and resurfacing, joint sealing, undersealing, slab replacement. Again, the choice of the appropriate repair technique depends on similar considerations as mentioned in the previous section.

1.4 Pavement Maintenance

The effort invested in pavement surface repairs like sealing of cracks, patching of potholes, chip and sand sealing, resurfacing with thin overlays, etc., is called pavement maintenance. This maintenance effort can be classified into two categories : routine and non-routine (or major) maintenance.

1.4.1 Routine Maintenance

This type includes the spectrum of day-to-day activities aimed at correcting the pavement distress, as it occurs, and which can affect traffic flow, user comfort or user safety. It includes items like patching of all types (shallow and deep, temporary and permanent, small and large); crack sealing (longitudinal, transverse, diagonal or whatever); seal coating (sand, chip, slurry or fog seals); and shoulder maintenance (full width sealing, clipping and blading).

1.4.2 Major Maintenance

This type includes treatments undertaken to avoid the evolution of surface deterioration that will pose a threat to the pavement's supporting structure thus requiring capital spending. It includes thin overlays; the application of extensive hot mix patching on significant portions of the road as required to address unavoidable situations resulting from poorly constructed localized areas; and drainage improvements needed to protect the integrity of the base and/or subbase from moisture attacks. Also included are other maintenance activities at isolated locations where external factors beyond the control of the highway agency have created problems -- factors like vandalism, spills, collisions and floods [Butler et al. 1986].

1.5 INDOT Routine Maintenance Activities

Indiana Department of Highways includes fourteen activities under its routine pavement and shoulder maintenance; these activities are described separately below. The description of the activities is based on the INDOT Field Operations Manual [INDOT 1984].

1.5.1 Shallow Patching (Activity 201)

Shallow patching is described as minor patching of small areas of the pavement or paved shoulder with hot or cold bituminous mixtures and hand tools to correct potholes, edge failures, and other potential surface hazards. It also includes temporary patching of bituminous and concrete surfaces and crack and joint spalling of concrete surfaces. This activity is basically aimed at removing hazards to traffic and to restore serviceability.

1.5.2 Deep Patching (Activity 202)

This includes major patching of roadway surface to correct extensive surface failure caused by base failure, blow up, or settlement. It includes, on all surface types, the full depth removal of surface and base material and replacement with compacted bituminous mixture. The major purpose of this activity is to remove major surface failures and distortions, thus improving safety and restoring serviceability.

1.5.3 Premix Leveling (Activity 203)

This refers to minor machine or hand leveling and wedging of small isolated areas of bituminous or concrete roadway and shoulder surfaces with hot or cold bituminous mixtures to correct depressions at bridge ends, surface failures and depressions caused by settlement at pipe replacements and deep patches. The main purpose of this activity is to remove dangerous driving conditions; correct minor crown deficiencies; correct for settlement between the paved shoulder and road surfaces; or adjust rutting and grade separations.

1.5.4 Full Width Shoulder Seal (Activity 204)

This refers to seal coating of continuous full width sections of paved shoulder surface with hot bituminous material and seal/cover aggregate. The main purpose of this activity is to correct extensive cracking, seal the surface to minimize moisture infiltration into the base, and/or restore shoulder life.

1.5.5 Seal Coating - Chip (Activity 205)

This refers to seal coating continuous full width sections of roadway surface with hot bituminous material and coarse aggregate. This activity is aimed at correcting extensive cracking, raveling, spalling or shallow surface failures; and to prevent deterioration of the pavement surface. This activity should be carried out only after the supporting activities (like squeegee sealing and patching) have been properly carried out.

1.5.6 Sealing Longitudinal Cracks and Joints (Activity 206)

This activity refers to the mechanical cleaning and sealing of longitudinal cracks and joints with liquid bituminous sealant to prevent entry of moisture and debris which leads to surface and base failure. It includes repairing the edge cracks between concrete surface and bituminous shoulder, any widening cracks and centerline joints. The main purpose of this activity is to protect the base and subgrade from moisture and foreign material -- thus protecting the infrastructure from serious disintegration.

1.5.7 Sealing Cracks (Activity 207)

This refers to the cleaning and sealing of open cracks and joints in bituminous and concrete roadways as well as paved shoulder surfaces to prevent the entry of moisture and debris which ultimately leads to surface and base failure. This activity also includes sealing short sections or isolated areas of alligatored, raveled, or spalled bituminous surfaces to prevent entry of moisture and further deterioration of the surface.

1.5.8 Seal Coating - Sand (Activity 208)

This activity refers to seal coating continuous full width sections of roadway surface with hot liquid bituminous material and fine aggregate (sand) to correct extensive cracking, raveling, and shallow surface failures and to prevent deterioration of the surface. This activity should be carried out only after the appropriate supporting activities (like squeegee sealing, patching or wedge and leveling) have been properly carried out.

1.5.9 Cutting Relief Joints (Activity 209)

This activity refers to the installation of relief joints in the pavement surface near the ends of bridge decks and approaches, where excessive blowups are occurring, or other locations where there is an indication of need, to allow expansion of pavement and structure. This activity is aimed at protecting the infrastructure from self desiccation.

1.5.10 Spot Repair of Unpaved Shoulders (Activity 210)

This activity refers to repairing small areas of unpaved shoulders by: adding aggregates, reshaping or compacting the existing ones for the purpose of correcting edge ruts, potholes and corrugations; and replacing lost material at washouts, around mailboxes, and public road approaches. The purpose of this activity is the removal of hazardous spots and locations.

1.5.11 Blading Shoulders (Activity 211)

This refers to reshaping aggregate shoulders to eliminate edge ruts, ridges, corrugations and high shoulders. The main purpose of this activity is to maintain safe emergency stopping conditions for the motoring public.

1.5.12 Clipping Unpaved Shoulders (Activity 212)

This activity refers to major clipping of overgrown shoulders to remove excess material and to restore proper slope for adequate drainage. It includes clipping of overgrown shoulders adjacent to the driving surface and sod adjacent to a paved or aggregate shoulder. Also includes related cleaning and reshaping of the adjacent roadside ditches as required.

1.5.13 Recondition Unpaved Shoulders (Activity 213)

This activity refers to reconditioning continuous sections of unpaved shoulders by adding aggregates, reshaping and compacting it in order to restore shoulder grade and surface. The purpose is safety of emergency stops and proper drainage.

1.5.14 Joint and Bump Burning (Activity 214)

This refers to heating and/or planing of bituminous surfaces to remove bumps, ripples and heaved joints. This effort is aimed at restoring the ride and pavement serviceability.

1.6 Major Issues and Concerns

INDOT is interested in evaluating the effectiveness of its routine maintenance activities. Three major and specific concerns were defined for this study : effectiveness of routine maintenance activities; value-for-money with respect to seal coating; and what policy guidelines (i.e. management criteria) to use for chip and sand seal coating decisions. Following is a brief discussion of each concern.

1.6.1 Effectiveness Of Routine Maintenance Activities

This concern can best be articulated in the form of a question: do routine maintenance activities make any difference in terms of the pavement's expected life, its serviceability to the public or safety of the motorists?

Two statistical approaches can be undertaken in answering this question. The first uses direct comparisons of before and after conditions for various groups receiving different treatments and identifying those groups having statistically significant changes. The second method calls for the calibration of performance functions of groups receiving different types of maintenance and the comparison of such functions. In reference to the first approach, the historical data on maintenance undertakings need to be, firstly, grouped by maintenance activity, location, highway type, facility age and condition; next, the differences in the performance of groups receiving an activity and a control group (not receiving any maintenance) are tested for statistical significance.

In reference to the second approach, the data for sections receiving no maintenance and those receiving a certain type of maintenance need to be, firstly, grouped; next, performance functions are developed using statistical regression techniques; and finally the resulting curves are compared to see if there appreciable difference among them exists.

A major dilemma that arises is whether lower order routine maintenance activities (e.g., patching, crack sealing, and joint sealing) should be applied at the early stages of distress as well as at the later stages when the distress becomes more obvious and severe. Another dilemma is under what conditions should higher order maintenance (e.g., seal coating) be considered as the primary strategy.

1.6.2 Value-for-Money

Higher order routine maintenance activities, such as sand and chip-sealing, are expensive, costing on average around 1000 and 2000 dollars (1987 $) per lane-mile, respectively. The main objectives behind carrying these activities are restoring skid resistance and protecting the investment in the infrastructure by extending its service life. If seal coating is applied too frequently or before needed, it is wasteful of funds; on the other hand, if it is delayed for too long, a surface may deteriorate to the point where a seal coating is not adequate to correct the deterioration and hence is wasted. There is obviously an optimal timing for its application. Answering the question of optimality of seal coating is not only a technical issue, but an economic one as well. Any strategy chosen for the pavement, including "do-nothing" has financial implications to the agency as well as the system users.

In addition, when the road has deteriorated too far, resurfacing with a thin overlay may be more cost-effective, if not essential. At what surface condition does resurfacing take over from seal coating as a best strategy is of continuing interest to highway agencies. The framework for evaluating cost-effectiveness is discussed in Chapter 3.

1.6.3 Policy Guidelines for Seal Coating

This concern revolves around the fact that, despite the expense of sand and chip seals, INDOT does not have explicit policy guidelines with regards to their use. There is keen interest for developing such policy guidelines in order to assist the Department's staff in making consistent decisions. Such guidelines would cover the following items:

a) When to use lower order routine maintenance and when to use seal coating; and

b) What type of seal coat (i.e., sand or chip) to use, and under what circumstances.

1.7 Regrouping of Routine Maintenance Activities for Evaluation Purposes

The fourteen maintenance activities used by INDOT are too fragmented for effectiveness evaluation purposes. It would be meaningful and productive if the 14 activities were regrouped in such a way that their effectiveness can become measurable and, hence, evaluable. Such regrouping should also take into consideration the data quality and limitations resulting from usable number of observations and there distribution among the districts. The data evaluation indicated that different regroupings were needed for flexible pavement, on one side, and for composite and rigid pavements, on the other. In the case of composite and rigid pavements, for example, the INDOT 14 activities were regrouped into 5 categories, based on the roles they play in the maintenance process, as shown in Table 1.1. Whereas in the case of flexible pavement, the 14 activities were regrouped into 4 interacting groups based on their association and complementarity in INDOT practice, as shown in Table 1.2.

1.7.1 Groupings of Rigid and Composite Pavement Maintenance Activities.

Each of the 5 major groupings is discussed separately below.

1.7.1.1 Patching

This category includes shallow patching (Activity 201), deep patching (Activity 202), and premix levelling (Activity 203). The main objectives for patching activities are to ensure safety of the motoring public and to protect the investment in the infrastructure. If the patches are not reasonably flush with the old pavement, however, patching could increase roughness. A major cost component of patching is the handling and placement cost, [O'Brien and Sinha 1985], improvements in work efficiency is a good route for reducing costs.

Table 1.1

Grouping of INDOT Routine Maintenance Activities for Evaluation Purposes For Rigid and Composite Pavements

AREA	ACTIVITY DESCRIPTION	ACTIVITY #
Patching	Shallow Patching	201
	Deep Patching	202
	Premix Leveling	203
Crack Sealing	Seal Longitudinal Cracks/ Joints	206
	Sealing Cracks	207
Joint Repairing	Cut Relief Joints	209
	Joint and Bump Burning	214
Seal Coating	Chip	205
	Sand	208
Shoulder Activities	Full Width Shoulder Seal	204
	Spot Repair:Unpaved Shoulder	210
	Blade Unpaved Shoulder	211
	Clip Unpaved Shoulder	212
	Recondition Unpaved Shoulder	213

Table 1.2

Grouping of INDOT Routine Maintenance Activities for Evaluation Purposes For Flexible Pavements

AREA	ACTIVITY DESCRIPTION	ACTIVITY #
Basic Routine Maintenance	Shallow Patching	201
	Deep Patching	202
	Sealing Longitudinal Cracks/ Joints	206
	Sealing Cracks	207
Premix Leveling	Premix Leveling	203
Chip Sealing	Chip Seal Coating	205
Sand Sealing	Sand Seal Coating	208
Shoulder Maintenance	Full Width Shoulder Seal	204
	Spot Repair: Unpaved Shoulder	210
	Blade Unpaved Shoulder	211
	Chip Unpaved Shoulder	212
	Recondition Unpaved Shoulder	213

1.7.1.2 Crack Sealing

Crack sealing includes sealing longitudinal cracks/joints (Activity 206) and sealing cracks (Activity 207). The main objective of crack sealing is to protect the structure of the pavement from further and faster deterioration. By so doing, the investment in the infrastructure is preserved. In the case of severe cracks, crack sealing can affect road roughness measurements as well.

1.7.1.3 Joint Repairing

This category includes two routine maintenance activities: cutting relief joints (Activity 209) and joint and bump burning (Activity 214). The objective of this activity group is to discourage the structure from self destruction due to climatic changes (moisture and temperature). By so doing, the investment in the infrastructure is protected. This activity also impacts the objective of driving safety.

1.7.1.4 Seal Coating

This group includes two activities: chip sealing (Activity 205) and sand sealing (Activity 208). These activities are employed to treat signs of raveling or erosion, oxidization of asphalt overlays, permeable surface development, or increased slipperiness. Hence seal coats are used to restore skid resistance, reduce road roughness and help protect the integrity of the pavement structure.

1.7.1.5 Shoulder Activities

This group includes five routine maintenance activities: full width shoulder seal (Activity 204), spot repair of unpaved shoulder (Activity 210), blading unpaved shoulder (Activity 211), clipping unpaved shoulder (Activity 212), and reconditioning of unpaved shoulder (Activity 213). Shoulder activities are intended in part to protect the investment in the pavement structure as in full width shoulder seal and spot repairs; and to improve safety as in blading the shoulder, clipping and reconditioning it.

1.7.2 Grouping of Flexible Pavement Maintenance Activities

The basic groupings for this type of pavement were derived from the maintenance cost and activity profile analyses. Following is a discussion of each group.

1.7.2.1 Basic Routine Maintenance

This group includes the lower order activities that are required to address the cracking and distribution problem of pavements. Since the repair of disintegration and skid hazard problems as practiced require that this activity group be carried out first, it has been called "basic". It includes crack sealing (Activities 206 and 207) as well as patching (Activities 201 and 202).

1.7.2.2 Premix Leveling

Premix leveling or wedging (Activity 203) involves placement of bituminous mixtures to correct depressions and rutting.

1.7.2.3 Chip Sealing

This includes the activity of chip seal coating (Activity 208). It is aimed at addressing problems of pavement disintegration or skid hazard locations. Its separation from sand seals (which serves a similar objective) was based on the objective of this study which is to evaluate the effectiveness of both types of seal coats and the fact that ample observations were procured in the area of flexible pavements which adequately covers both activities.

1.7.2.4 Sand Sealing

This includes the activity of sand seal coating (Activity 205). This activity is aimed at the same problem areas mentioned in section 1.7.2.2 above.

1.7.2.5 Shoulder Activities

This group includes five activities: Full width shoulder seal

(Activity 204), spot repair of unpaved shoulder (Activity 210), Blading unpaved shoulder (Activity 211), clipping unpaved shoulder (Activity 212), and reconditioning of unpaved shoulder (Activity 213).

1.8 Research Scope and Structure

This study will address the three issues or concerns mentioned in Section 1.6 above. In addressing the first issue, namely whether maintenance makes any difference, the before/after statistical evaluation technique was used; for quantifying the impact, the General Linear Model (GLM) was used. For addressing the second issue, namely evaluating the cost-effectiveness of chip and sand seal coating, the life cycle costing technique was employed. For dealing with the third concern, namely the development of policy guidelines for the use of seal coating, INDOT expert opinion survey, telephone interviews with other State transportation agencies, and personal interviews of key INDOT staff were carried out.

The work is presented in eight more chapters. Chapter 2 is a literature review of studies undertaken in the areas of routine maintenance and cost-effectiveness evaluations in Indiana and the rest of the U.S. Chapter 3 is the development of the evaluation framework of the three issues including the economic evaluation of seal coating. Chapter 4 is an explanation of the design of this experiment, the collected data and file structure. Chapter 5 is the summary of the statistical evaluation of the gathered data. Chapter 6 is the detailed study and economic evaluation of seal coating activity. Chapter 7 deals with the development of the recommended policy guidelines for seal coating. Chapter 8 deals with the requirements of the proposed long term monitoring program for routine maintenance activities. And, finally, Chapter 9 is the summary of the study conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

For building a basic information base for this study, a literature review was carried out in three areas: 1) the routine maintenance roles and impact measures; 2) effectiveness evaluations of routine maintenance activities in Indiana; and 3) Other studies on the evaluation of routine maintenance effectiveness. A summary of the review is presented in this chapter and is structured according to the above sequence.

2.1 Routine Maintenance Roles and Impact Measures

Routine maintenance is generally carried out for any of the following three objectives:

a. to protect the investment in the infrastructure by controlling or reducing the rate of pavement deterioration;

b. to improve pavement serviceability through the elimination of roughness and the sources of hazard to motorists (e.g., blow-ups and potholes); and/or

c. to improve driving safety on wet pavements by increasing the pavement's skid resistance.

Although each of the five routine maintenance activities is carried out for a primary purpose, impacts on the other objectives do occur, as well, to produce secondary outcomes. These secondary outcomes are sometimes positive and, at other times, negative. For example, while crack sealing is carried out primarily for protecting the infrastructure from worse and more rapid deterioration, it could reduce roughness -- a positive secondary impact. When applied extensively, crack sealing can reduce skid resistance -- a negative secondary impact. Another example can be found in patching; although patching may be carried out for safety purposes by eliminating potholes, it may often (if not properly finished) increase road roughness, which is a negative secondary impact.

Management of service delivery programs, such as highway maintenance, takes the sequence of the key activities illustrated in Figure 2.1. Objectives are first set; resource levels are identified; repair activities are then chosen; outputs like patched lane-miles or sealed linear miles of cracks are produced; and when consumed by the users, certain outcomes are obtained (e.g., more comfortable ride, safer driving conditions, reduced operating vehicle operating costs). There are other non-user outcomes that relate to the agency as well, such as increased service life of pavements and deferred capital spending. The above mentioned outcomes can be subdivided into two groups: objective related outcomes and secondary outcomes.

Evaluating the physical effectiveness of the various routine maintenance activities is essentially checking whether the activities have achieved their intended purposes. This assessment relates the outcomes to the objectives, as shown in Figure 2.1. Cost-effectiveness evaluation approaches the assessment of maintenance activities from a different angle, namely financial and economic. Here, the intent is to check if the obtained benefits and outcomes are worth the money spent on achieving them. The outcomes in this circumstance would therefore include both objective and non-objective related outcomes, whether positive or negative.

Based on a number of references [Asphalt Institute 1983, CalTrans 1983, MTO 1985, APWA, INDOT 1984], the following tabulation summarizes the roles of the five activities, where P stands for primary and S, for secondary:

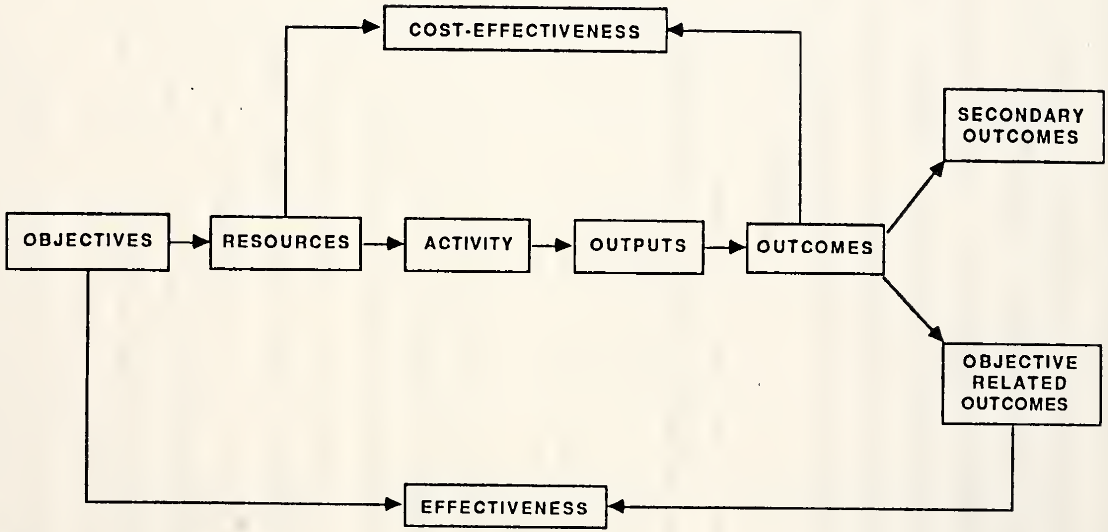


Figure 2.1

Effectiveness and Cost-Effectiveness Evaluation Comparison

ROUTINE MAINTENANCE ACTIVITY	PROTECT THE INFRASTRUCTURE	IMPROVE GENERAL SAFETY	IMPROVE SKID RESISTANCE
Patching	P	P	S
Crack Sealing	P	S	S
Joint Sealing	P	P	S
Seal Coating	P	S	P
Shoulder Activities	P	P	S

In the literature review, measurement of the impact of routine maintenance on the protection of the infrastructure was quantified using some measure of pavement surface condition. Such measures, which are a function of the manifested distress, were expressed in different ways by different organizations; for example, PAVER uses PCI (Pavement Condition Index) [Army 1982]; Ontario uses PCR (Pavement Condition Rating) [Ontario 1987]; and Indiana uses PSR (Pavement Serviceability Rating) [INDOT 1988]. PCR and PCI vary from 0 to 100, with 0 being the worst and 100 the best. PSR varies from 0 to 5, 5 being the best. Furthermore, the distress scoring itself can vary from extreme sophistication in measurements (Paver's PCI) to a quick windshield survey (Indiana's PSR); or it could be somewhere in the middle (Ontario's PCR).

As to the quantification of the impact of maintenance activities on pavement serviceability, three different approaches have been used: one related roughness to maintenance effort [Sharaf and Sinha 1984]; another related change in roughness to maintenance effort [Al-Suleiman and Sinha 1988]; and the third, in terms of PSI-ESAL Loss [Fwa and Sinha 1988].

2.2 Effectiveness of Routine Maintenance Evaluation in Indiana

A number of research studies were carried out in this area by the Joint

(Purdue University/Indiana DOT) Highway Research Program. These studies focused on the prediction of some effects of routine maintenance, as described below:

2.2.1 Routine Maintenance and Pavement Characteristics Study

Sharaf and Sinha [1984] examined the relationship between the level of routine maintenance and pavement characteristics. Routine maintenance cost prediction models were developed to estimate the total annual maintenance costs per lane mile as a function of age and accumulated traffic for rigid and flexible pavements. However, pavement condition was not included nor were the results adequately related to the need for resurfacing.

In addition, separate models were developed to estimate future patching and crack sealing costs. These models highlighted a strong relationship between crack sealing costs on the one hand and climate and traffic level (in terms of ESAL), on the other. It also highlighted a strong relationship between patching costs and traffic level as well as the level of crack sealing carried out. A by-product of the above study was a set of average unit cost matrices for eight routine maintenance activities (averages for 4 years) detailed by climatic region (North and South), highway class and pavement type.

2.2.2 Aggregate Damage Model for Highway Pavement Performance Study

Fwa and Sinha [1988] developed an aggregate damage model for highway pavement performance analysis which resulted in the introduction of the concept of PSI-ESAL loss as an indicator of pavement deterioration and loss of serviceability. This parameter (instead of the traditionally used PSI) offers a quantitative measure of historical performance. The concept of zero-maintenance curve was also introduced as a reference level for quantifying the impacts of various routine maintenance effort levels. Another finding was the identification of two climatic zones with significant difference in their impacts on performance (North and South). An issue relating to the measurement of the effects of routine maintenance on pavement performance was resolved by using a measure called pavement routine maintenance effectiveness index, M; that measure proved to be significant only in the case of flexible pavements. The study in general focused on the effect of total routine maintenance expenditure rather than the individual activities within routine maintenance.

2.2.3 Procedure for Assessment of Routine Maintenance Needs Study

Montenegro and Sinha [1986] proposed a procedure for the assessment of routine maintenance needs. Unlike the traditional procedure of estimating by past trends, the proposed procedure was based on a unit foreman's evaluation of highway deficiencies, as these deficiencies are conceived at the time of the evaluation. The development of the procedure included regression models utilizing both subjective and objective data.

2.2.4 Life Expectancy of Routine Maintenance Activities Study

Feighan et al. [1986] estimated the life expectancy of routine maintenance activities based on a stratified random sampling survey of maintenance personnel at the subdistrict level within Indiana. The study documented estimates of service lives, accomplishments per day and unit costs of various routine maintenance activities for three roadway conditions (poor, average and good). The study, however, did not consider the effects of traffic and climate.

2.2.5 Impact of Routine Maintenance on Pavement Surface Condition Study

Al-Suleiman and Sinha [1988] analyzed the impact of various levels of routine maintenance (measured in terms of expenditure) on pavement surface condition and consequently on pavement service life. The effects of three factors (pavement age, traffic loading and climate) on highway pavements were considered. The incremental change in roughness and the rate of change in roughness were investigated. The study made use of covariance analysis. The data consisted of two quantitative variables (pavement age and cumulative equivalent single axle load) and two qualitative variables (climatic region and routine maintenance category). The relationship between roughness and these variables was found to be curvilinear; this was equally true of the relationship between rate of change of roughness and climatic regions and routine maintenance levels. The database of this study was limited: only one year maintenance expenditure was considered and not all routine maintenance activities were included.

2.3 Other Studies on Effectiveness Evaluation of Routine Maintenance

Interest in the evaluation of routine maintenance effectiveness is not restricted to Indiana only, but extends to many other states and countries as well. Here is a brief summary of some of the studies reviewed.

2.3.1 The HDM-III

The Highway Design and Maintenance Standards Model [World Bank 1985], was developed for evaluating the implication of various construction and maintenance strategies based on their interplay with road user costs. For each year of the analysis period, the traffic submodel first computes the traffic for each link for the analysis year. The road construction submodel then checks the traffic loading against the threshold level or calendar year and initiates road construction accordingly. Based on that decision, it calculates the construction costs and changes the road characteristics as required. The road deterioration and maintenance submodel then takes over and predicts for each year the amount of deterioration (using roughness as a measure of road condition) as well as the quantities and costs of maintenance work in terms of existing pavement conditions, maintenance standards, traffic loading, and environmental conditions. To estimate the deterioration and these quantities and costs, the surface distress is first calculated by damage function (such as cracking, raveling, pot-holes, ruts); by pavement type and classification; by probability and by sublink. It then proceeds to calculate the roughness increment in the analysis year by components (traffic, surface distress, age/environment) and by sublink. Once the condition is known, it checks if periodic maintenance is scheduled and, if the answer is positive, proceeds to compute the change in condition and maintenance quantity by type of treatment (e.g., reconstruction, overlay, reseal, preventive). If no scheduled major maintenance exists, it checks if the developing conditions justify such action; if the answer is positive, it carries similar calculations as described earlier. If the answer is negative, it checks if routine patching is required, and if the answer is yes, it calculates the change in condition and maintenance quantity by patching. It then sums up the maintenance costs for that year and calculates the output average roughness, and inputs it in the vehicle operating cost submodel for the calculation of road user costs. The post maitenance condition, strength and age are lastly computed for input into the next analysis year and the whole process is repeated. The model generates three types of cost outputs: construction, maintenance and road user costs. Various strategies can then be compared to each other in terms of costs, and in terms of the resulting road conditions as well.

2.3.2 RTIM2

The Road Investment Model for Developing Countries was designed by the British Transportation Road Research Laboratory [Parsley and Robinson 1982] to assist engineers and planners "to study various aspects of a road investment project such as the optimum maintenance standards for the road; the effects of providing an earth, gravel, or bituminous pavement; or the differing benefits that can be obtained by adopting various staged construction options". Given a specified analysis period, the model starts at year 0 and calculates construction costs using either the built in functions or user supplied costs. The next step in the model is traffic forecasting. Based on the predicted traffic, vehicle information input and maintenance standards desired, it determines the road surface condition; the user costs including, time, fuel and oil, parts, tires, crew, depreciation and other overheads; and the road maintenance costs using patching, surface dressing and overlaying for paved roads or other strategies for other pavement types. It repeats the calculations for each year and at the last year of the analysis period, it uses the user input discount rate to compute the present worth of all costs. The user can specify a number of discount rates to check for the sensitivity of his assumed rate.

2.3.3 EAROMAR - 2

The Economic Analysis of Roadway Occupancy of Freeway Maintenance and Rehabilitation [Butler, Jr. 1974] is a life cycle costing computer program that uses built-in, predefined cause/effect relationships (such as damage functions) as well as user specified inputs (such as pavement characteristics, unit costs, maintenance and rehabilitation strategies). The pavement is subjected to the user specified conditions and its performance is predicted, by distress type, based on the built-in damage functions. If the maintenance strategy is varied, the performance varies and should be re-evaluated. Such analysis can be performed with a number of strategies and service levels for the purpose of identifying the best strategy. A later development, EAROMAR Version 2 [Markow and Brademeyer 1984], addressed some shortcomings that existed in the earlier version and expanded the model's capabilities. The drawback of this model was that the basic maintenance data required to modify the damage functions to become sensitive to maintenance were not available; hence, these damage functions related more to rehabilitation strategies than to maintenance strategies.

2.3.4 SHRP (H-101) -- Pavement Maintenance Effectiveness Study

The thrust of this project [SHRP 1987] is to develop a data base that will permit increased understanding of selected maintenance treatments in extending pavement service life or reducing the evidence of pavement distress; evaluate the effectiveness of the pavement maintenance treatments; and establish a study methodology that can be followed by highway agencies to evaluate other maintenance treatments. The study selected the "controlled experiment" approach to evaluate the performance effectiveness of six specific preventive maintenance treatments: chip seals, thin overlays, slurry seals and crack sealing for flexible pavements; joint and crack sealing as well as undersealing for rigid pavements. The primary factors to be considered include traffic volumes, environment, pavement characterization, and pavement condition at the time of application. The experimental design for rigid pavements utilizes a multi-tier approach (three in total). These tiers help filter the effects of a wide range of factors (climate, structural design, subgrade type, traffic, condition at treatment, drainage, and so on) that interact in a complex manner to influence pavement performance. The first (primary) tier factors relate to environmental, loading and subgrade considerations; it specifically includes the following parameters with their corresponding levels shown inside the brackets: subgrade (fine and coarse), traffic (medium and high), temperature (freeze and non-freeze), and moisture (dry and wet). The secondary tier factors relates to pavement design characteristics; it specifically includes slab thickness (low and high), subbase (granular/untreated, cement stabilized/econocrete base, and bituminous stabilized), and subdrainage (none and yes) for all of JPCP, JRCP and CRCP pavements. JPCP gets one extra factor for analysis, namely load transfer (doweled and undoweled), whereas JRCP gets transfer joint spacing (short and long) as its extra factor, but not load transfer. The third (secondary) tier focuses on the condition of pavement and maitenance treatments; it helps to assess the treatment effects. Factors considered in this tier include pavement and shoulder condition (slight/good, moderate/fair, and severe/poor, whichever description fits best), shoulder design (AC, tied PCC, wide traffic lanes), joint and crack filling (apply and do not apply), undersealing (apply and do not apply), and control (no treatment). The study is at the national scale and is now in the phase of data gathering.

2.3.5 The Illinois Study

A joint study between University of Illinois and Illinois DOT [Dwiggins et al. 1989] analyzed Interstate Highway pavement performance using data collected by the Illinois Pavement Feedback System (IPFS). In particular, the study focused on the analysis of performance of two major pavement design types: continuously reinforced concrete pavements (CRCP) and jointed reinforced concrete pavements (JRCP). Special attention was also given to the study of "D" cracking. The study assumed that pavements deteriorate due to both traffic loading (TESAL) and age -- where age was used as a surrogate measure to represent cycles of freeze/thaw, hot/cold, wet/dry the pavement is subjected to in its lifetime. Both variables were hence taken as indicators of the useful life of pavement, common to both types (CRCP and JRCP). The distribution of the estimated percentage of total pavement length (by age or ESAL) that have been overlaid for the first time were calculated using the product limit (or Kaplan-Meier) method found in the SAS Statistical Analysis Software [SAS, 1985]; this method is also known as the survival curve technique.

2.3.6 The Oakland (MTC) Study

This effort [Darter et al. 1984] focused on the study of the cost effectiveness of maintenance and rehabilitation treatments. The study used available data at the network level as decision criteria and developed a simple "decision tree" network level assignment procedure. The life cycle cost analysis was used to determine the most cost-effective treatments. Five major cost components were included: initial maintenance/construction costs; future maintenance costs; salvage value at end of analysis period; traffic delay user cost during maintenance/construction closures; and extra user costs of vehicle operation, time, accidents, and discomfort due to increased roughness. Although the procedure allows for the inclusion of all these costs, user costs and salvage value were ultimately excluded in the initial application because of the difficulty of their estimation in a reliable manner. The treatments that were evaluated include rejuvenating seal, slurry seal, single chip seal, double chip seal, thin asphaltic concrete overlay, and thick asphaltic concrete overlay. Streets were divided into two groups: residential and arterial. Life expectancies and impacts on service life were estimated using an expert opinion survey and the consultant's staff experience. Four types of conditions were distinguished based on the overall condition measures and whether the distress was load related or not. The life cycle cost analysis procedure made use of the equivalent uniform annual cost (EUAC) method.

The procedure at the section level was followed by a network assignment procedure based on two key decision factors: traffic level (functional classification) and pavement condition. The objective of the study in this endeavor was to establish feasible, cost effective maintenance target rather than optimal allocation of funds. Some of the major findings in the study include: 1) the average long-term annual cost is much higher when the pavement is allowed to deteriorate; 2) for any given pavement condition of the four types in the study, there is considerable difference in average annual costs for different maintenance strategies; 3) the most cost-effective maintenance strategy depends on both the pavement condition and traffic; and 4) complete reconstruction and thick overlays appeared to be poor choices for most applications.

2.3.7 The Utah Study

This study [Anderson et al. 1980] was a joint venture between Utah DOT and FHWA to investigate the cost effectiveness of pavement rehabilitation design strategies. The model framework used has four phases. Phase 1 is a Pavement Condition Analysis Module which considers the pertinent data to the various highway sections and identifies the deficient sections that need further analysis in Phase 2. Phase 2 is a Matrix Interface Module where appropriate maintenance and rehabilitation strategies are selected for the candidate sections. The Individual Pavement Benefit/Cost Module of Phase 3 calculates the benefits and costs of each strategy for each link and ranks the strategies in relation to each other. Phase 4 is the Collective Pavement Benefit/Cost Module, where strategies are selected on a network basis. The economic evaluation method includes five costs: cost of rehabilitation, delay costs during improvement, user and maintenance costs over the life cycle of the pavement until further rehabilitation is required, as well as the salvage value at the end of the cycle. The study utilized relationships tieing user cost to pavement serviceability index (PSI) and maintenance cost to PSI and pavement age, by class of road. Although the study was designed for rehabilitation strategy analysis, it can be modified to handle seal-coating strategy analysis. Since maintenance costs are related to condition (PSI), there would be no need to develop new cost functions. Yet, the study has two limitations: firstly, the accuracy of the available relationships between user costs and pavement condition is questionable, even as admitted by the authors; secondly, the costs are limited to Utah's circumstances which could be significantly different from those of Indiana.

2.3.8 The Jamaica Study

The model used in this study was developed by a U.K. consultant for Jamaica's Ministry of Public Works [Weatherell and Ebrahim 1987]. It was intended to compare and evaluate four main strategies for pavement maintenance: routine maintenance, resealing, overlay, and "rip-up and reseal". It used data gathered in the developing world including Jamaica. Threshold curves were used for defining the boundaries between strategies, with such curves being plotted against average daily traffic and roughness, thus providing a simple visual display of the decision space for each choice (see Figure 2.2). The study used a number of surrogate measures (such as traffic served as a surrogate for social and economic travel). It also assumed that all accrued benefits are due to savings in vehicle operating costs for the main roads and increase in agricultural productivity for feeder roads. The net present value economic evaluating technique is used as the basis for financial analysis.

2.3.9 The Washington State Study

This study [Jackson, et al. 1990] was carried out in response to the many complaints (dust, delays and windshield damage) against chip seals applied in the western part of the state in 1988. These chip seals were applied mainly to roads with 2000 ADT or less. Inspection of the seals revealed four common problems: flushing, windshield damage, aggregate loss and excessive aggregate use. Consequently the study focused on methods of construction and material specifications. The information for evaluation was obtained in three ways: meetings were held with each district staff to discuss their individual experiences with chip sealing projects, both good and bad; a questionnaire was sent to each project engineer involved with the work; and each project was reviewed by at least one member of the study team. The study explained the potential causes of the above mentioned problems and offered guidelines for their arrest. Most of the recommendations address methods and materials of construction as well as methods for quality and traffic control, but there were some recommendations with respect to management criteria:

> "... To make chip sealing programs more cost-effective and palatable to the traveling public, other methods of system preservation should be considered where:

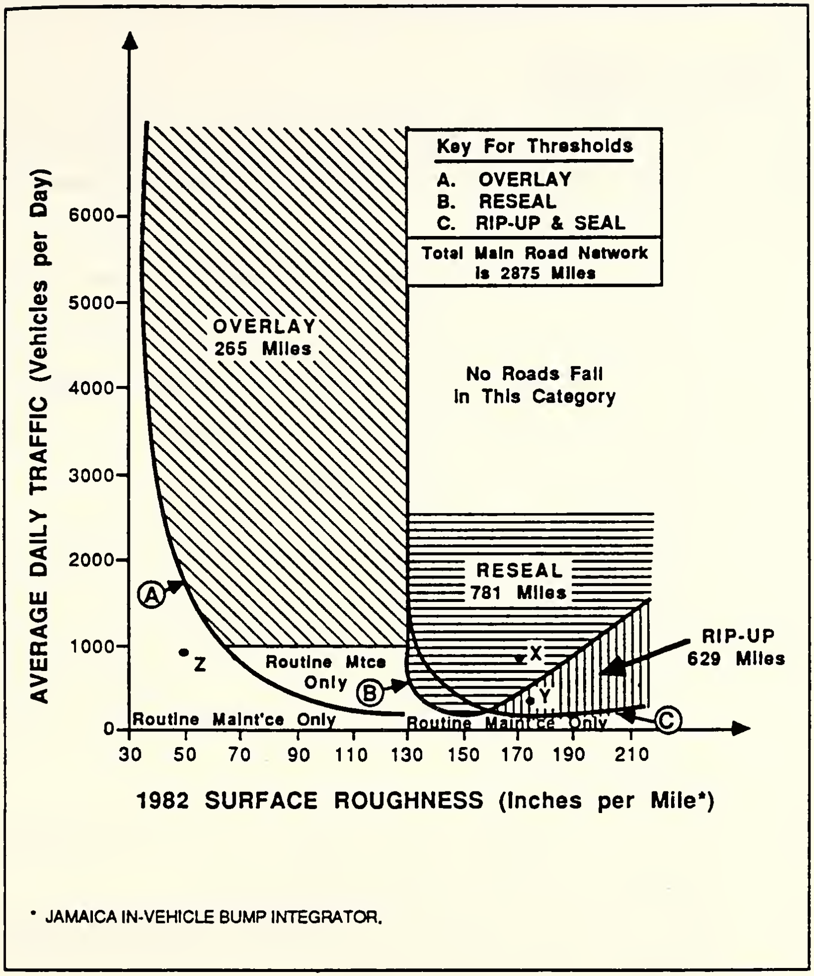


Figure 2.2

Threshold Curves Developed in the Jamaica Study

[Source: Wetherell and Ebrahim 1987]

a. the ADT exceeds 5000; and/or
b. the truck percentage exceeds 15 without regard to ADT levels between 2000 and 5000 vehicles per day."

2.4 Summary of Findings

To summarize, the above studies have pointed to a number of useful leads into the area of cost-effectiveness evaluation of routine maintenance activities. These include the following:

a. that roughness and pavement serviceability index are reasonable measures of pavement performance, namely the serviceability aspect;
b. that routine maintenance does have an impact on roughness;
c. that the cumulative ESAL is more important as an indicator of pavement condition than the annual ESAL or AADT;
d. that factors such as age, thickness of slab and climate are not only important as main effects, but also as interacting effects;
e. that various maintenance activities have effect on each other;
f. that the effects of routine maintenance on pavement performance have so far been analyzed within short periods of time, but not within longer periods;
g. that the average long-term annual cost is much higher when the pavement is allowed to deteriorate; and
h. that the most cost-effective maintenance strategy depends on both pavement condition and traffic.
i. that the effectiveness of seal coatings depends on road conditions when applying seals; on materials, their mix and handling; as well as traffic controls.

CHAPTER 3

EVALUATION FRAMEWORK

The three major concerns or issues mentioned in Chapter One require different types of evaluation techniques and analysis frameworks. For this reason, the current chapter is structured by issue or concern.

3.1 Evaluation of Routine Maintenance Effectiveness

The determination of whether routine maintenance activities make a difference on pavement serviceability, condition or skid resistance, and to what extent, depends on statistical analysis, on the one hand, and engineering judgement and experience, on the other. The former provides numerical evidence of significance (or conversely, the lack of it), and the latter provides physical meaning and justification to the numerical results.

In the way of answering these two questions, a three step strategy was adopted:

1. Preliminary testing of data validity;
2. Application of before/after comparisons of groups receiving maintenance and those not receiving any (control groups); and
3. Application of Generalized Linear Model (GLM) procedures to quantify the relationships among the selected dependent and independent variables.

Following is a description of each step.

3.1.1 Preliminary Testing of Data Validity

To ensure the validity of the data, a number of checks can be employed. These include: sorted lists subjected to visual scanning and comparisons; cross tabulations; and plots of scatter diagrams of the various data against time and select key variables. To illustrate, sorted lists by climatic region, district, subdistrict, and highway class can be useful in checking consistency of data and coding errors. Cross tabulations are good for preparing descriptive summaries. Plots of activity profiles (such as maintenance activity expenditure versus age or cumulative loading, by climatic region, by function, by surface type) can be used to develop understanding of these profiles and to detect the presence of performance and expenditure trends, the strength of the trends and their nature (that is, linear or curvilinear).

3.1.2 Before/After Comparisons

The before/after comparison is a test whereby two groups are selected: one receiving a certain type of treatment and the other, a control group, receiving no maintenance. The means of the indicators of performance (such as RN,PSR, Skid N) are calculated for each of the two groups before and after action. The changes in the means of the two groups are then compared and tested for statistical significance. If the activity tests as significant, then adequate evidence in the data that the particular maintenance activity being evaluated does make a difference is said to exist. If no significance is detected, then one of two possibilities exist: either the activity does not, in reality, make any difference or the differences that.the activity makes are too small to be detected within the error margins of the existing data. In the latter case, engineering judgement and experience play a major role, for it may be misleading to conclude that the activity is useless. To carry out a meaningful evaluation of this type, the analyst has to ensure that, if a certain routine maintenance activity (or a group of activities) is being evaluated, the effect of the other activities is not present. If this requirement is not satisfied, then the effects of the factors being evaluated and the ones that are not are said to be confounded; hence, no definite conclusions on the effects of the desired activities can be reached. To illustrate, when evaluating the effect of patching, this filtering takes the form of selecting the sections that received patching only during a particular period, and nothing else, or those that comprise the control group, i.e., those receiving no maintenance whatsoever during the same period. If the joint effect of patching and seal coating is being evaluated, only those sections that received patching and seal coating, but nothing else, along with the control group are included. In this case, the maintenance costs of both activities are added as one maintenance cost, since the activities are now considered as one. This filtering process needs to be carried out before testing every activity or combination of activities.

Activity groupings for rigid and composite, and flexible pavements have been presented in Table 1.1 and 1.2, respectively. The combinations tested are indicated in Tables 3.1 and 3.2 for rigid and composite pavements, respectively. Table 3.3 is for flexible pavement tests. These runs were repeated for all of the three dependent variables: roughness number, pavement surface rating and skid resistance number, all of which are continuous variables, that is, they could take any real value.

This type of testing is most effectively carried out by using a statistical technique known as the Generalized Linear Model (GLM) procedure, part of the Statistical Analysis System (SAS). This procedure is robust and allows for the testing of the significance of the effects of various factors (class or continuous type) describing the section (such as, age, climate, and so on) on its

Table 3.1

Combinations Tested for Rigid Pavements

RUN NO.	PATCHING (201, 202, 203)	CRACK SEALING (206, 207)	JOINT SEALING (209, 214)	SHOULDER ACTIVITIES (204, 210, 211, 212, 213)
One Activity At A Time				
1	x	-	-	-
2	-	x	-	-
3	-	-	x	-
4	-	-	-	x
Two Activities At A Time				
5	x	x	-	-
6	x	-	x	-
7	x	-	-	x
8	-	x	x	-
9	-	x	-	x
10	-	-	x	x
Three Activities At A Time				
11	x	x	x	-
12	x	x	-	x
13	x	-	x	x
14	-	x	x	x
All Activities At A Time				
15	x	x	x	x

Table 3.2

Combinations Tested for Composite Pavements

RUN NO.	PATCHING	CRACK SEALING	SEAL COATING	SHOULDER ACTIVITIES
One Activity At A Time				
1	x	-	-	-
2	-	x	-	-
3	-	-	x	-
4	-	-	-	x
Two Activities At A Time				
5	x	x	-	-
6	x	-	x	-
7	x	-	-	x
8	-	x	x	-
9	-	x	-	x
10	-	-	x	x
Three Activities At A Time				
11	x	x	x	-
12	x	x	-	x
13	x	-	x	x
14	-	x	x	x
All Activities At A Time				
15	x	x	x	x

Table 3.3

Combinations Tested for Flexible Pavements

Maintenance Group	Maintenance Activities
GROUP 1	Basic Routine Maintenance (Activities 201, 202, 206, 207)
GROUP 2	BRM + Chip Sealing (Activity 208)
GROUP 3	BRM + Sand Sealing (Activity 205)
GROUP 4	BRM + Premix Leveling (Activity 203)
GROUP 5	Shoulder Maintenance (Activities 204, 210, 211, 212, 213)
GROUP 6	BRM + Shoulder Maintenance
GROUP 7	BRM + Chip Sealing + Shoulder Maintenance
GROUP 8	BRM + Sand Sealing + Shoulder Maintenance
GROUP 9	BRM + Premix Leveling + Shoulder Maintenance

performance (that is, RN, PSR, SkidN, and so on). Eight independent variables were included in the present study for rigid and composite pavements and 5, for flexible. Tables 3.4 and 3.5 show these variables, their symbols, levels and the definitions used for specifying their levels per pavement type. Since the means of groups can be calculated by class, all of the independent variables were converted to class variables.

The model used in the testing of significance of the independent factors for rigid and composite pavements was of the form:

$$\begin{aligned} \textit{Dependent Variable} = {} & (T + M + E + F + R + P + Q + I) + \\ & \{T{*}I + T{*}E + T{*}Q + T{*}R + T{*}P + T{*}F\} + \\ & T{*}M + [T{*}M{*}E + T{*}M{*}F + T{*}M{*}R + T{*}M{*}P \\ & + T{*}M{*}Q + T{*}M{*}I] + T{*}M{*}E{*}F + T{*}M{*}E{*}F{*}I; \end{aligned}$$

where,

- the parameters within the first brackets, (..), represent the main factor effects;
- the parameters within the second brackets, {..}, represent the effect of before and after measurement variation attributed to the main factors other than maintenance;
- T*M represents the effect of before and after measurement variation attributed to the selected maintenance;
- the parameters within the third brackets, [..], represent the effect of before and after measurement variation attributed to the interaction of maintenance and the other section descriptors;
- T*M*E*F represents the effect of the before and after measurement variation attributed to the interaction of maintenance with the class and location of the sections; and finally,
- T*M*E*F*I (which applies to rigid pavement only) represents the effect of

Table 3.4

The Independent Variables and Their Levels
for Rigid and Composite Pavements

INDEPENDENT VARIABLES	NO. OF LEVELS	DESCRIPTION
Test (T)	2	0, for a reading before treatment 1, for a reading after treatment
Maintenance (M)	2	0, not receiving the activity 1, for receiving it
Class (E)	2	1, for Interstate Highways ISH 2, for Other State Highways OSH
Location (F)	6	1,2,...,6, for district number
Thickness (R)	2	1, for thin (K<=9") [Bumphrey 1989] 2, for thick (K > 9")
Age (P)	3	1, for young (age <= 12 yrs.) 2, for medium (12 < age <= 18 yrs) 3, for old (age > 18 yrs)
Loading (Q)	3	1, for low (TESAL<=1.5 million) 2, for medium (1.5M<TESAL<=3.0M) 3, for high (TESAL>3.0 millions)
Design Type (Rigid Only) (I)	2	1, for JPCP 2, for JRCP
Climatic Region (G)	2	0, for north (Laporte,Fort Wayne) 1, for south (other 4 districts)

Table 3.5

Independent Variables and Their Levels for Flexible Pavements

Independent Variables	No. of Levels	Description
Maintenance (M)	2	0, if no maintennace received 1, if maintenance received
Location (F)	6	1,...., 6 district number
Traffic (Q)	3	1, for low [ESAL<=15,000 -OSH* ESAL <= 100,000 -ISH** 2, for medium [15,000 <ESAL <= 25,000 -OSH, 100,000 <ESAL <= 300,000 -ISH] 3, for high [ESAL>25,000 -OSH ESAL>300,000 -ISH]
Age (P)	3	1, for young [age <= 10 yrs - OSH, age <= 5 yrs, -ISH] 2, for medium [10 yrs < age <=20 yrs -OSH, 5 yrs < age <= 10 yrs -ISH] 3, for old [age > 20 yrs -OSH age > 10 yrs -ISH]
Climatic Region (G)	2	0, for north [Laporte, Fort Wayne] 1, for south [other districts]

* OSH = Other State Highways
** ISH = Interstate Highways

before and after measurement variation attributed to the interaction of maintenance, class, location and design type.

The model used to test the significance of the independent variables on the change of pavement condition for flexible pavements was of the form: where,

$$\Delta RN,\ \Delta PSR = \begin{array}{l} (M + F + Q + P) + M*F \\ + M*Q + M*P \\ + (F*Q + F*P + Q*P) \\ + M*F*Q + M*F*P \end{array}$$

- ΔRN represents the change in pavement roughness measurements between 1984 and 1987.
- ΔPSR represents the change in pavement serviceability rating between 1985 and 1987.
- M represents the effect of the selected maintenance on variation in the change of pavement condition.
- the parameters "F", "Q" and "P" represent the effects of pavement section location, mean annual equivalent single axle load and pavement age, respectively, on variation in the change of pavement condition.
- the parameters (M*F), (M*Q) and (M*P) represent the effects of the interaction of maintenance and other section descriptors on variation in the changes in pavement condition.
- the parameters (F*Q), (F*P), and (Q*P) represent the effects of variation in the change of pavement condition attributed to the two-way interaction of the other pavement contract section descriptors.
- (M*F*Q) and (M*F*P) represent the effect of variation in the changes of pavement condition attributed to the three-way interaction of maintenance and other pavement contract section descriptors.

The parameters of interest are those that start with T*M since it represents the before/after variation attributed to maintenance only or to maintenance interaction with other parameters; the parameters within the first and second brackets are not of concern to the study but had to be included in the model for statistical reasons. The term "interaction of two variables" implies a joint effect of both variables on the dependent variable. This kind of effect is detected when there is systematic variation of the means among the various combinations of the levels of the two interacting variables.

For any of the above parameters to be declared definitely significant, the probability greater than the F-value (P>F, using the adjusted sum of squares- Type III which accounts for the effects of all the independent variables on each other) has to be less than or equal to 0.05; if the P>F lies in between 0.05 and 0.10, the significance is said to be marginal; and if P>F value is greater than 0.10, the parameter is considered as "not significant".

3.1.3 Quantifying the Impacts

The use of linear regression technique assumes that the errors are normally distributed and their variance is homogeneous, that is, their distribution around the mean error does not systematically vary with the variation of the predicted value of the dependent variable. If they do, the problem can be sometimes solved by transforming the dependent variable. However, if the required transformation is complex, it may not be wise to carry it out. The assumptions underlying linear regression techniques need to be verified in the data before their usage. Tests of normality and homogeneity of variance of the input data would, hence, be required. Again, the GLM procedure can be used to develop the equations relating the required maintenance effort to pavement characteristics and attributes, and to relate pavement performance to the section attributes.

3.1.4 Developing Pavement Condition Envelopes

The regression procedure of SAS was used to develop the relationships between pavement serviceability (PSI) and age of pavement for various groups of maintenance activities and by climatic region. The same statistical assumptions applicable to section 3.1.3 above also apply here. Once these functions are developed, they are plotted and their plots are directly compared.

3.2 Evaluation of Cost-Effectiveness of Seal Coating

Cost-effectiveness evaluation is an economic evaluation technique for comparing "that which is sacrificed (cost) to that which is gained (effectiveness) for the purpose of evaluating alternatives" [Kazanowski 1966]. It generally includes those procedures and concepts that involve comparing input costs to outcomes, whether priced or not ; such outcomes (results) can be benefits, returns, satisfaction or progress towards goals [Winfrey and Zellner 1971]. Cost-effectiveness analyses proceed on the basis that, although the cost can be presented in dollars, the effectiveness of these costs in producing desirable goals and results can be described only in qualitative statements because not all the benefits and adverse consequences can be presented on a dollar basis. In brief, cost-effectiveness analysis applies to those areas where the consequences of the input costs cannot be dollar priced. Cost-effectiveness evaluations are sometimes used to provide a summary statement on a given activity or to provide some insight into how to improve the activity effectiveness and delivery. The first application is known as "summative" and the latter, "formative". In a summative mode, cost-effectiveness evaluation of routine maintenance activities is concerned with whether a given activity is worth the amount of resources expended on it. In a formative mode, such evaluation is concerned with the appropriate use of the activity and its optimal timing. Since both aspects are of interest, each of these will be discussed separately below.

3.2.1 Cost Effectiveness : Summative Evaluation

Whether a certain maintenance activity is worth its costs depends on whether the treatment of the problem is essential; whether the action treats the problem and to what extent; and whether the value of the benefits equals or superceeds the costs, when the effects of money utility over time has been accounted for.

Whether a given treatment is necessary or not is a function of the level of service the public expect, the type of problem being treated and the engineering properties of the pavement itself. To illustrate, whether the distress is a pothole or a crack has certain implications on the need to take action; potholes need to be immediately patched for safety reasons and because the public generally do not accept to live with them, whereas sealing of cracks is needed to seal the pavement from the infiltration of the moisture to its substructure. If that substructure is well drained (e.g., gravity drainable to less than 50% saturation in less than 1 hour), then sealing the crack may not be all that essential because the moisture will quickly drain from the subbase anyway. In financial terms, this action is labeled by some as economic waste.

On the other hand, cracks can be of different types: some may have been caused by shrinkage; others, by fatigue; and some others, by poor construction joints; to name only a few examples. If the crack is a fatigue crack, then the above argument can be justifiable. However, if the crack is a shrinkage crack, it can be conversely argued that leaving the crack open will allow the ingress of incompressibles which, in turn, forbids the pavement from expansion with temperature fluctuation. The fact that the shrinkage crack occurred in a slab does not necessarily mean that the pavement does not need some space for expansion when temperature increases. If that crack is not sealed with the appropriate material and incompressibles were allowed to get in, the slab may blow up. Hence, sealing the crack in this case is essential.

Now turning to whether the action will treat the problem and to what extent, the answer depends on the nature of the problem and the durability of the materials used to correct it. Considering the same "cracking" example, if the cracks are fatigue caused, crack sealing is not likely to arrest the problem; such cracks will continue to develop despite any crack sealing activity. On the other hand, if the cracks are shrinkage cracks, crack sealing could be effective because climate caused pavement adjustments are periodic and not continuous. As to how long the seal lasts depends on the properties of the material used. Rubber mixed seals for example, have different properties and, hence, different life expectancies than silicon seals.

The above logic applies to seal coating as well. As cited earlier, seal coats are applied to pavement surface for one of three main reasons: to restore surface friction; to restore an oxidized, raveled or weathered surface; or to seal mild alligator cracking. The first two are surface related problems; the last can sometimes be a surface related phenomenon and, at other times, surface and base related problems. Historical maintenance records at INDOT do not include information on the types of distress that led to the decision to sealcoat; the only information available is the composite indicators (such as RN

& PSR). By necessity therefore, the study had to be limited to the aggregate approach.

As to the economic aspects of how benefits and costs compare, cost-effectiveness can be operationally approached from two angles: one is to seek the maximum benefits for a given level of investment (hence the maximum benefit approach); the other, to seek the least cost for the effective treatment of problems (least cost approach). The first approach is more appropriate for capital investment evaluation; the second, more appropriate for maintenance investment evaluation. The explanation for this dichotomy is simple. For capital projects, the single investments involved tend to be large and bear great elements of uncertainty; consequently, the assessment of the exact costs and benefits is very difficult. In addition, the measures of effectiveness are difficult to choose and relatively more complex to define due to the effect of the timing of expenditures, their resulting benefits, as well as the spill over effects. However, in maintenance, the single expenditures are relatively smaller in value and generally incurred in the shorter run; their impacts are more immediate and concentrated in a small area. When the field engineer, for example, is faced with a distressed pavement, the problem is first diagnosed and a number of potential solutions are considered. On the basis of resource constraints, the solutions are narrowed down to a few choices, whose costs can be determined with a fair degree of confidence. The choice that yields the cost-effective solution is the one that minimizes the overall costs.

Least cost in maintenance management has been defined in one of two ways: the first, as the least present worth of total life cycle cost divided by the expected life of the solution [Chong and Phang 1983]; and the second, as the least annualized total life cycle cost, calculated in perpetuity. The first is an averaging technique that does not have any valid engineering-economics basis whereas the latter is more exact in its treatment of costs and benefits as they occur over time. The second approach was therefore used in the present study. The costs considered in the life cycle analysis included annual maintenance costs (such as patching and crack sealing), periodic seal coating costs, annual user costs and future resurfacing costs. The above discussion is summarized in Figure 3.1.

3.2.2 Cost Effectiveness : Formative Evaluation

Formative evaluation of cost effectiveness focuses on the identification of the optimal timing of seal coats. This can be achieved by analyzing the performance of a one lane-mile of highway subjected to different maintenance strategies as well as the costs associated with these strategies. Since the expected life of a seal coat depends on the original condition of the pavement before seal coating, it will be assumed that the decision to seal coat the given lane-mile of highway at the selected point in time is valid from an engineering sense and, hence, the seal coat will last the corresponding expected service life. The life cycle cost (which includes agency and user costs) can be computed for a variety of maintenance strategies and/or conditions: with or without seal coats; seal coating at various roadway conditions; seal coating for various usage levels; and so on. The seal coating life cycle cost envelope for various threshold levels can be plotted. The minimum life cycle cost in that envelope determines the optimal timing. This approach requires the identification of the agency costs (annual maintenance costs; periodic seal coating costs; and future resurfacing costs) and vehicle operation costs for each timing option. The resulting variance in life expectancies of the pavement section due to different

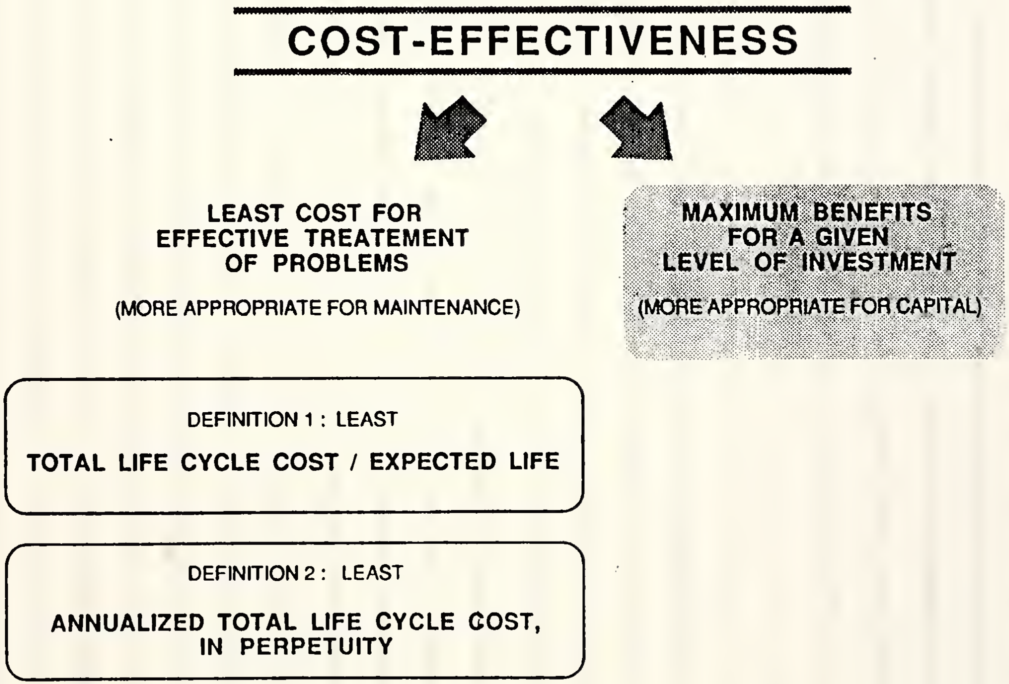


Figure 3.1

Approaches to Cost-Effectiveness Evaluation timings will be taken care of by discounting in perpetuity.

Forming the guidelines for seal coating management involves engineering and economic aspects. Section 3.3 sets the framework for developing the guidelines which are fully described in Chapter 7.

In closure of this section, it is worth remembering that for cost-effectiveness analysis to be possible, three necessary conditions need to be satisfied [Kazanowski 1968]:

a. identifiable and attainable goals or purposes must exist (seal coating goals may include safety of the motorists; preservation of the pavement; delaying resurfacing);
b. there must be alternative means for meeting the goals (options being: only low order maintenance; seal coats; do nothing); and
c. there must be perceptible constraints for bounding the problem (certain activities may be applicable only to pavements of a certain age and condition or not more than four seal coats may be applied in between resurfacings).

The first condition is required in order to have a basis for comparison; the second, to have a comparison; and the third, to be able to make a choice (whether on the basis of cost, time and/or effectiveness parameters).

3.3 Developing Policy Guidelines for Seal Coating

Any developed policy guidelines for managing seal coating activities have to satisfy a number of requirements. The guidelines should:

a. have sound engineering and economic basis;
b. make use of existing experience within and outside of Indiana;
c. be able to give guidance in making decisions, while maintaining

flexibility;

d. be easy to understand and implement;

e. accommodate organizational constraints both resource and operational; and

f. be consistent with other existing policies and practices of different field units.

Developing a set of policy guidelines meeting all of the above criteria automatically implies an interactive process of development, discussion and revision. The development of the guidelines was structured in three stages: first, developing a general overview of what knowledge and experience has accumulated across U.S. and Canada; second, documenting Indiana's current practice; and third, formulating a decision tree on the basis of the findings of other parts of this study with what was gained in the first two steps.

3.3.1 Developing a General Overview

To develop a general idea on the state of practice of seal coating in North America, many research methods can be used. For example, literature reviews can give summaries of specific experiences, experiments or points of view of the agency publishing the literature. Phone interviews with officials within state highway agencies can give a better understanding of the "real" state of the practice, as opposed to published information. Phone interviews with officials from research institutions can yield useful comparative evaluations of state practices and policies. Operation manuals of state agencies are also useful because they give a good idea about the written intent behind and the reasoning underlying their practices. All of the above techniques were used in the present study.

3.3.2 Indiana's Practice

To develop an overview of the current practice in Indiana, a number of sources were tapped. First, the staff of INDOT has a tremendous reservoir of information; personal interviews augmented with an expert opinion survey of INDOT District Managers and key Central Office staff brought forward a fair amount of that knowledge. Second, there are annual Surface Change Reports, prepared by INDOT Research Division, that contain information on surfaces that have been resurfaced or seal coated; a summary of these reports provided a quantification of the extent of the practice. Third and last, the findings from the present study were available, particularly as related to optimal timing and cost-effectiveness of seal coating strategies.

3.3.3 Development of Policy Guidelines

Any engineering activity is generally managed by guidelines at three hierarchical levels (as illustrated in Figure 3.2): first, broad statements defining the spirit of action and the general direction for the activity; second, management criteria that give some benchmarks and yardsticks to district maintenance engineers against which they can gauge their decisions whether to seal coat or not, when, and to what extent; and finally, specific instructions on what materials and practices are acceptable to the agency.

A general review of INDOT's Field Operations Handbook for Foremen [INDOT 1984] revealed that the State has some policy guidelines for defining the usefulness and general applicability of chip and sand seal coating. The State also has a set of specifications in this regard that defines the acceptable materials, application rates, construction techniques, among other things [INDOT 1985]. However, "management criteria" have been found missing. Hence, the present

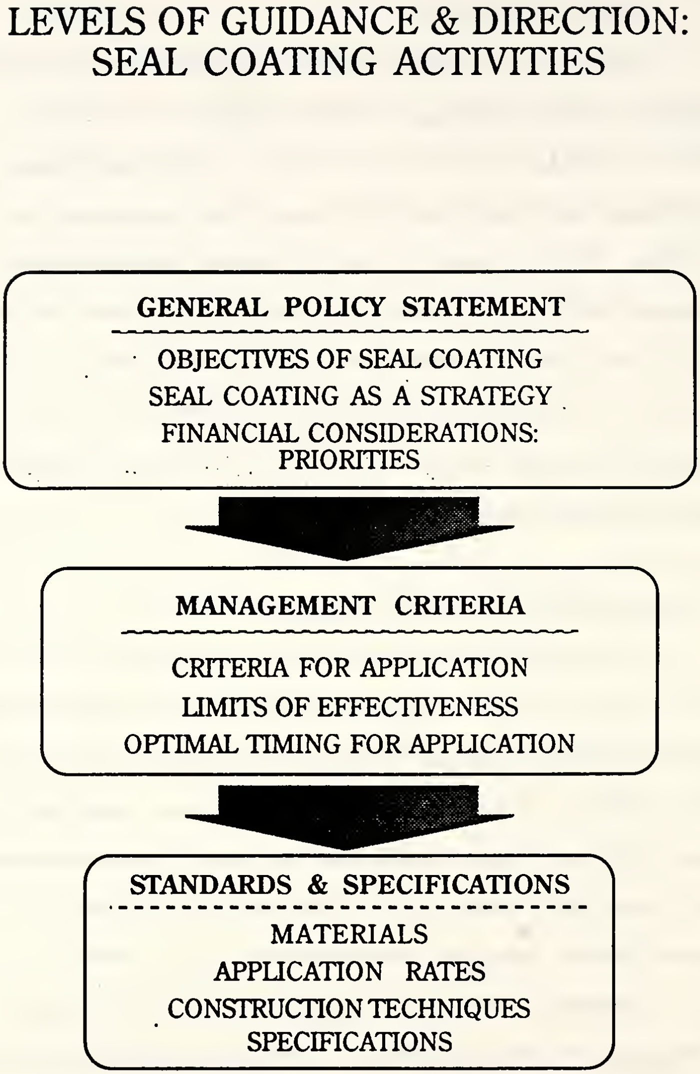


Figure 3.2

Three Levels of Guidance and Direction to Seal Coating Activities study focused on filling in the gap by developing a set of criteria that can be used for making seal coating decisions at the district level.

There are many factors that influence the decisions regarding whether to seal coat or not; when; and to what extent. These factors include engineering considerations pertaining to the condition of the pavement structure and surface; climatic characteristics such as freeze/thaw conditions and the extreme temperature difference; age of the pavement and the usage it has been subjected to, such as traffic and snow plows; road priority (could be function of class and/or role); and the availability of funds for capital and maintenance. The most compact form for dealing with so many factors is the decision tree, because it eliminates irrelevant decision choices quickly and efficiently. Hence, the management criteria were developed in the form of a decision tree.

3.4 Concluding Summary

In this study, three related issues were raised: the effectiveness of routine maintenance practices; value for money for seal coating; and what management criteria to use for chip and sand sealing. Evaluating these issues necessitates separate approaches, each requiring a different evaluation structure. The first issue was evaluated primarily through statistical analyses of before and after data. The second issue was considered through a life cycle engineering economic analysis. And finally, the third issue involved a policy oriented approach. The results of these three evaluation frameworks are presented in Chapters 5, 6 and 7, respectively.

CHAPTER 4

DESIGN OF THE EXPERIMENT AND DATA BASE

Based on the previous discussion and the findings of earlier studies, a number of significant factors had to be considered in the evaluation of maintenance effectiveness. For successful evaluations, appropriate data and information related to these factors were required. The manner in which the data and information were to be sampled was also important because it affects the type and extent of inference from the sample to the whole population. This chapter discusses the influential factors that affect performance, the sampling procedure used and the various sources of information from which the databank was developed.

4.1 Influencing Factors

A number of factors were found to provide explanations to the variation in pavement performance and/or the impact of maintenance on such performance, as discussed below.

4.1.1 Pavement Type

Different materials have different engineering behavior and characteristics. Whether the pavement is flexible rigid or composite determines what type of performance profile to expect. In addition, concrete pavements are constructed differently: pavement slabs are sometimes built continuous and, at other times, jointed; and either plain concrete or reinforced concrete. Again the engineering behavior and performance of these types can be, and often is, different from one to the other. The three types of concrete pavement construction used in Indiana are: "plain concrete" (PCP), "jointed reinforced concrete" (JRCP), and "continuous reinforced concrete" (CRCP). In this study, five different types of pavements were included (1 flexible, 3 concrete types and 1 composite) as illustrated in Figure 4.1.

4.1.2 Highway Classification

The functional classification of a highway is an indicator of the role that highway plays in the movement of people and goods. Interstate highways (ISH), for example, are intended as national links to move high volume of traffic and heavy trucks over long distances. Other State highways (OSH), which include US Highways and State Roads, tend to move local traffic within the State, provide essential access and carry moderate traffic. Some of these were observed to carry light traffic and others, heavy traffic. In addition, the two types of highways are built based on two different sets of structural and geometric standards. They also receive different levels of maintenance. In order to capture the differences in design, usage and care for these facilities, highway class was used as a variable, with two levels: ISH and OSH.

4.1.3 Pavement Thickness

The structural capacity of the pavement is directly related to its thickness. The thinner the pavement slab, the lower is its bending moment capacity and the higher is its susceptability to cracking by fatigue. Therefore, pavement thickness is a good indicator of cracking potential, under certain loading conditions.

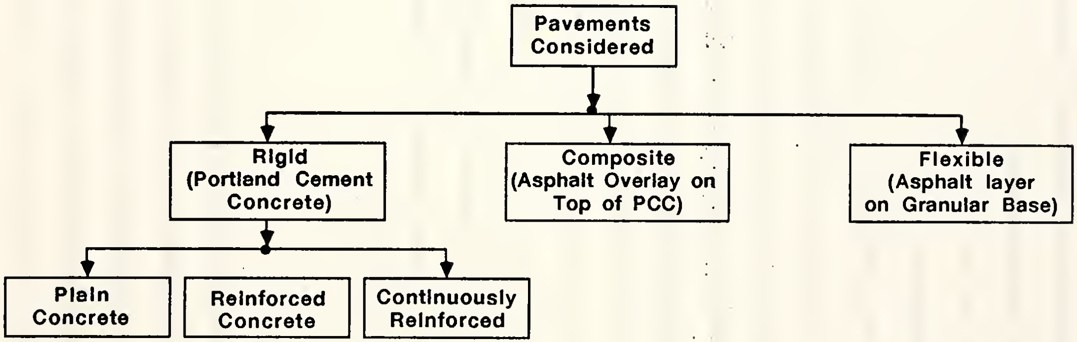


Figure 4.1

Types of Pavement Considered in the Study

4.1.4 Climate

Pavements in cold climate have been observed to behave differently than in warmer climate. Freeze-thaw cycles tend to create volume changes in the surface aggregates, base and subgrade. Surface problems resulting on rigid pavements are known as "D" cracking. Volume changes in the surface of composite pavements can cause shrinkage cracking. Subgrade moisture can create heave under the slabs thus creating rough ride and unsafe driving conditions.

Fwa and Sinha [1988] investigated the effect of climate on pavement performance and concluded that Indiana can be divided into two climatic zones, North and South, with significant differences in their impact on pavement performance. The two zones are shown in Figure 4.2. In this study, these two climatic zones were recognized as two experimental classes.

4.1.5 Location

The soil composition and the depth of water table vary from one part of Indiana to another. In addition, the available materials vary (such as in quality of quarries and hence quality of aggregates used) from location to location. Practices, as well, differ from area to area in the State thus causing variations in the costs of construction and maintenance. Since most routine maintenance decisions are made at the subdistrict level, as opposed to the State level, a variable is required to capture such variation. INDOT has six districts, five of which have six subdistricts and one has seven subdistricts. Each subdistrict has 3 to 4 maintenance units that actually do the work and are controlled by a subdistrict maintenance engineer. The decisions, therefore, are controlled at the subdistrict level. As a result, the subdistrict was considered as the appropriate management unit, and as a good indicator of the location to location

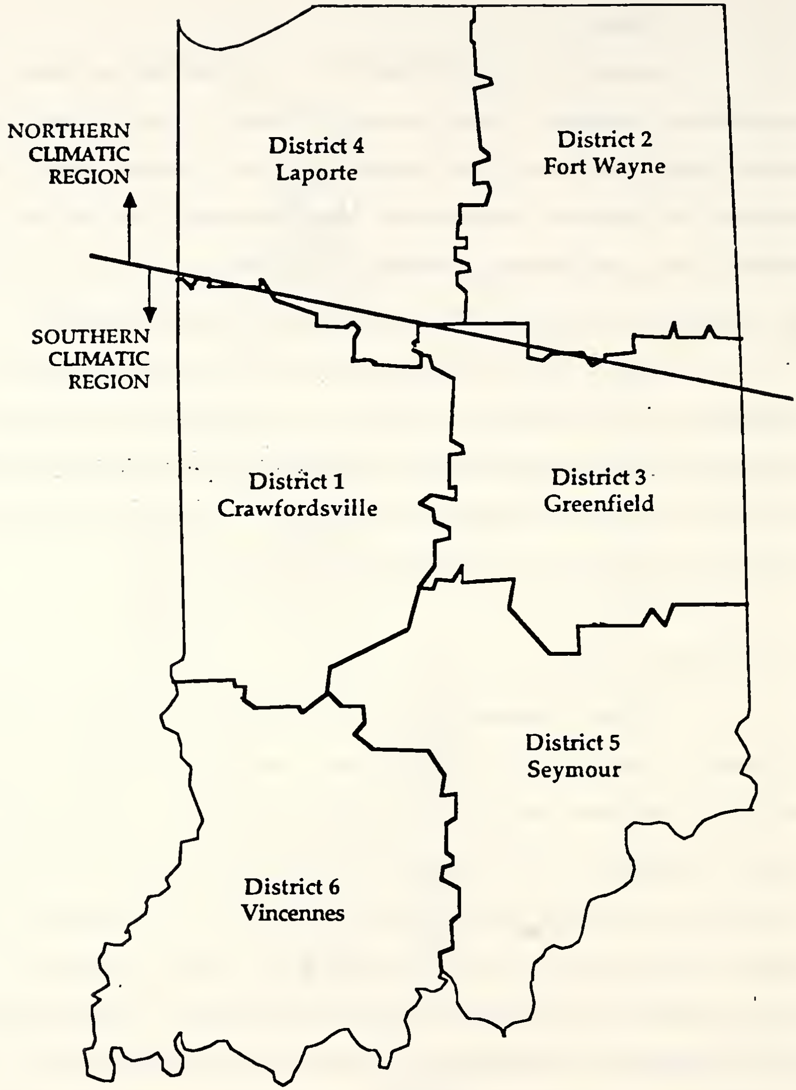


Figure 4.2

Map Illustrating the Boundaries of the Two Climate Zones in Indiana variation.

4.1.6 Age

All materials wear with age. Over time, asphalt oxidizes and becomes brittle, thus becoming more susceptible to cracking, particularily when subjected to heavy loading. PCC pavements can suffer from a phenomenon called "Carbonation". Under such phenomenon, carbon dioxide from the air interacts with the upper 1/4" to 1/2" surface of the pavement and weakens it. The slab becomes susceptible to erosion and breakage. Also the bond within the concrete or asphalt itself gets weakened by natural changes such as freeze-thaw cycles and wet-dry condition fluctuation. Age was hence chosen as one of the variables.

Since the above described phenomena start when materials are laid down on site, age of the pavement is measured from the last date of resurfacing, not from the date of initial construction.

4.1.7 Usage

Repeated loading and unloading of the pavement can cause it to fail by fatigue. Hence, the total amount of traffic that the pavement is subjected to over its life since last laid down is a very significant determinant of the pavement condition [Sharaf and Sinha 1984; Fwa and Sinha 1988]. Traffic, anywhere, is far from being homogeneous (that is, normally composed of small passenger vehicles, pick-up trucks, buses, trucks and tractor-trailers, and so on). Furthermore, the effect of a heavy truck is much greater than that of the much lighter passenger vehicles. Consequently, a common measure needs to be developed.

The AASHO Road Test [HRB 1962] in the sixties proposed the conversion of the various loadings imposed on the pavement by vehicles of different loads and axle configurations to one common measure, based on their effects on the pavement. The Equivalent Single Axle Load (ESAL) was chosen as common measure. The effect of an 18 kip single axle load was taken as a base and all other effects were derived from comparing the effects of any load to the effect of that 18 kip axle. The ESAL was adopted and used in the present study.

In this current study, the annual traffic was first obtained for each link from the INDOT's traffic reports; the traffic data were then converted into ESAL using an established procedure [Sharaf and Sinha 1984]. The annual ESAL values were then summed over the life of the pavement (since last resurfacing) to obtain a total ESAL, TESAL. The level of the TESAL is a good indicator of surface distress.

A large TESAL, however, can result either from a high volume of heavy loading during a relatively short period of time (as is the case of ISH) or from a low volume of heavy loads over a relatively longer period of time as illustrated in Figure 4.3. Consequently, both "Age" and "TESAL" were included as two separate parameters in the present study.

4.1.8 Routine Maintenance Level

The level of maintenance given to a pavement affects its surface condition. The phrase "a stitch in time saves nine" applies. If the initial cracks were promptly sealed, the base and subgrade would be protected from surface moisture; otherwise, the moisture would weaken the support under the pavement and more severe distresses would develop, particularily in a freeze zone. Earlier studies [Sharaf and Sinha 1984; Al-Suleiman and Sinha 1988] confirmed the validity of maintenance level as an explanatory factor of pavement performance. Hence "pavement maintenance" was used as an independent variable.

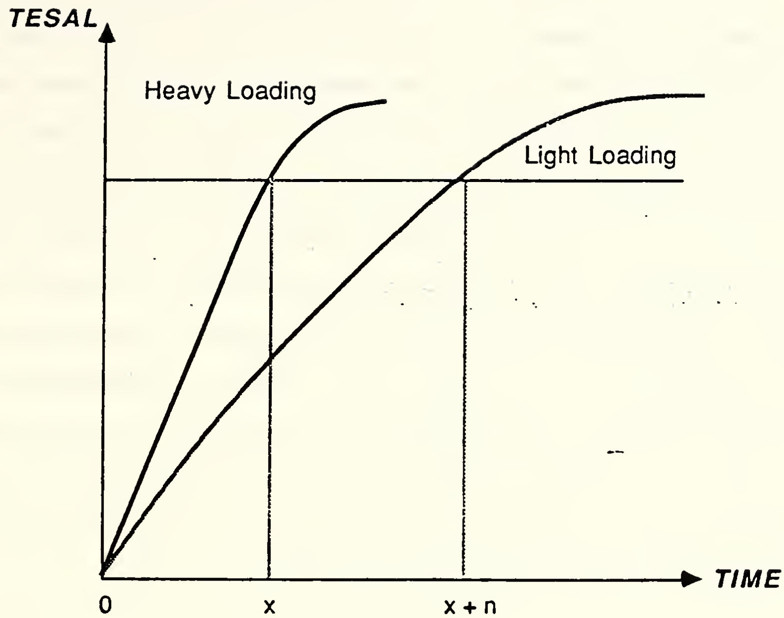


Figure 4.3

Illustration of the Effect of the Type of Loading on the Accumulated ESAL

To summarize this section, eight influential factors were chosen for analysis in this study; these factors are: pavement type, road function, pavement thickness, climate, location, age, usage, and maintenance level.

4.2 Dependent Variables

Pavement performance can be assessed in terms of one of three indicators: the pavement's serviceability, condition or safety. The first indicator, "Pavement Serviceability" has been expressed by an index (PSI) that was based on the road's rideability as perceived and judged by a panel. PSI, however, has been directly correlated to road roughness. The second indicator," Pavement Condition" has been traditionally measured in terms of the amount of surface distress; it has been expressed in different units by different organizations: Pavement Surface Rating (PSR), Pavement Condition Rating (PCR), or Pavement Condition Index (PCI). The third and last indicator, "Pavement Safety", is normally measured in terms of the pavement's skid resistance quality. The three indicators of performance are discussed separately below.

4.2.1 Road Roughness

Road Roughness is a good indicator of the pavement's serviceability which is affected by the amount of routine maintenance the pavement receives. Roughness testing in Indiana is performed with a PCA Roadmeter. This device was developed by the Portland Cement Association in the early 1970s. The rationale underlying the use of this technique is that road roughness ought to be measured in terms of what the passenger feels rather than what the actual road profile is.

The Roadmeter is installed in a mid-sized car and driven at 50 MPH over the desired highway section; the results are reported by mile and contract.

The roughness number, RN, is a measure of the square of the number of 1/8" movements of the autobody with respect to the rear axle. For example, if the car passes over a rough spot that raises the car 1" out of its normal plane of motion, this is recorded as eight one-eighth inch "bumps" squared. The car, of course, does not move up one inch and return to rest, but rather the "bump" is dampened by the springs and shock-absorbers to reduce the vertical acceleration of the passengers. In addition, the actual bump on the road may be much larger than one inch. RN can vary from as low as 50 counts per mile to as high as few thousands, depending on how smooth or rough the road is.

A number of factors (such as speed of vehicle, odometer calibration number, shock absorber type and temperature, tire type and pressure, fuel tank level and displacement transducer spring tension) can interfere and affect the validity of field measurements. INDOT Research Division had addressed this problem at an earlier date and developed a set of adjustment equations that are still in use. These equations are applied and what is called the "Adjusted Roughness" is recorded. The roughness numbers were converted to a per lane-mile basis. These adjusted figures were used for analysis in the present study.

Three variables were investigated, the first was the roughness level itself; the second, the change in roughness,

$\Delta RN = RN(after) - RN(before)$

and the third is the rate of change in roughness,

$\text{Rate of } \Delta RN = [RN(after) - RN(before)]*100 / RN(before)$

4.2.2 Surface Distress

Another aspect of the pavement that gets affected by maintenance is the state of distress the pavement displays. INDOT carries out an annual windshield survey of pavement condition of all state highways. Department staff drive on all ISH and OSH sections and give them ratings that vary from 0 to 5 based on their distress and roughness of ride, with 5 being the excellent condition. Such ratings are known as Pavement Serviceability Ratings (PSR); they are kept in the Road Life Records (Highway Inventory).

Again three variables were investigated: the first was the PSR level itself; the second was the change in PSR,

$\Delta PSR = PSR(after) - PSR(before)$

and the third was the rate of change in PSR,

Rate of $\Delta PSR = [PSR(after) - PSR(before)]*100 / PSR(before)$

4.2.3 Pavement Safety

The attribute of the pavement that contributes to safety is its skid resistance ability. It has been reported [Moyer 1971] that a high degree of correlation exists between the total number of accidents on a given section of a highway and the coefficient of friction as measured by a standard test method. Normal total accident rates reported by many studies for various road conditions can be summarized as follows:

CONDITION	FRICTION COEFFICIENT	ACCID./MILL VEH-MI
Dry Pavement	> 0.60	1.00 - 3.00
Wet Pavement	0.30 - 0.40	2.00 - 6.00
Slippery When Wet	0.15 - 0.25	15.0 - 20.0

"Skid resistance" is a quantity reflecting the amount of friction that exists between the pavement surface and the tire of the vehicle. It therefore varies with the properties of both the pavement surface and tire and with the speed of their interaction. The friction significantly varies by pavement surface type due to different textures and friction coefficients of portland cement and asphaltic concretes; by wet and dry condition of the pavement (as illustrated in the above table); and by vehicle speed.

For dry pavements, skid resistance coefficients are fairly high and the range of variation is narrow; in contrast, wet pavements can have high or low skid resistance figures (but definintely lower than their values when dry) and a wide range of variation [Whitehurst 1968]. The speed of braking of the vehicle determines whether there is adequate time for the water to squeeze out from under the tire, that is, whether or not hydroplaning is going to occur. Braking speed is determined by a number of factors that interact in a complex way. Such factors include traffic characteristics, geometrics, driver attitude and behaviour, to name only a few.

Skid Resistance (expressed in SkidN -- skid number -- purposefully chosen to differentiate it from SN, the structural number) is quantified in Indiana in accordance with ASTM Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire (E274). Since skid resistance can have short term variation due to rain, as shown in Figure 4.4, tests are carried out for the worst condition. Hence, testing here involves measuring the longitudinal force required to drag a locked wheel, non-rotating tire over a wet pavement. Wetness is artificially created when the truck dragging the trailer delivers a controlled amount of water in front of the test wheel. Special instrumentation is needed for the measurement of the drag force. This testing approach is referred to as "Locked Wheel Trailer Method".

Having the drag force and the vertical load determined, the Skid Number is calculated as follows:

$$\text{Skid N} = 100f = 100F / L, \quad \text{where}$$

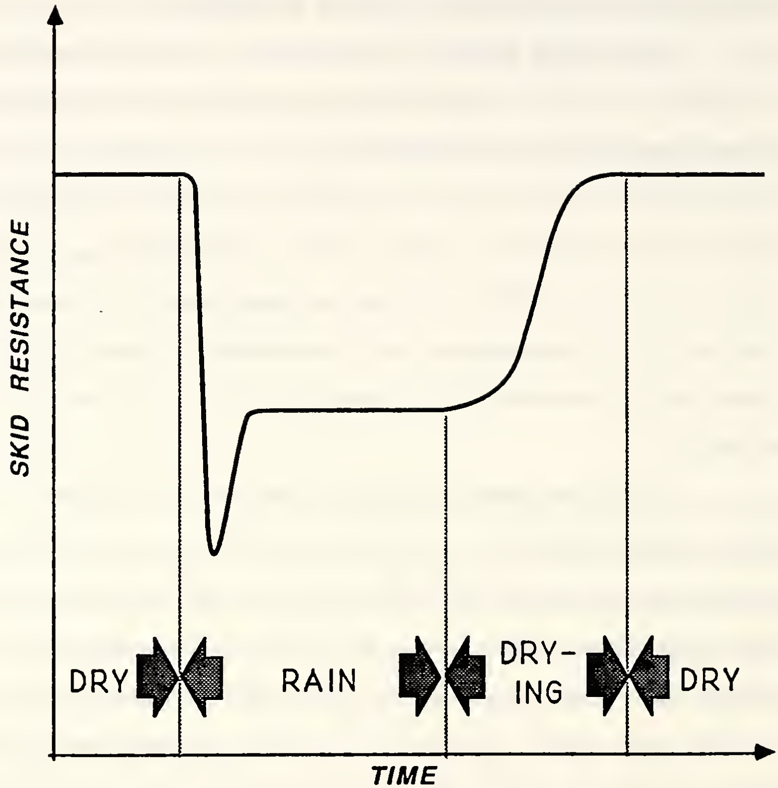


Figure 4.4

Example of Short-Term Changes in Skid Resistance
Due to Rain

[Source: NCHRP Synthesis Report 14, 1972] f - friction factor,

F - frictional resistance, and

L - vertical load.

Again three variables (the Skid N level itself, the change in Skid N, and the rate of change in Skid N) were initially investigated, but the required data were not consistently available.

4.3 Sampling Technique

As mentioned earlier, Indiana has six districts and 37 sub-districts; the subdistrict represented the most appropriate management level. In order to have a representative sample across the State, a stratified two-stage sample survey was selected for the study. In the first stage, two sub-districts were randomly selected from each of the six INDOT maintenance districts, thus resulting in twelve sub-districts (in total) as shown in Figure 4.5. In the second stage, a sample of road sections was picked from each selected sub-district. This latter sample was selected in such a way as to adequately represent: Inter-State and Other State Highways; rigid and composite pavements; old and new pavements; as well as high and low usage levels.

Since the line demarking the boundaries of the two climatic regions does not neatly follow the boundaries of the districts, the subdistricts were treated as "nested" factors within the climatic regions, with the intent of using "contrasts" for comparison of district to district variations. All other factors were considered crossed with each other. Figure 4.6 shows the experimental layout.

Tables 4.1, 4.2 and 4.3 show summaries of the number of selected contracts distributed by pavement type; by function (ISH and OSH); by climatic region; and by location. As time progressed from 1984 to 1987, some of the selected rigid

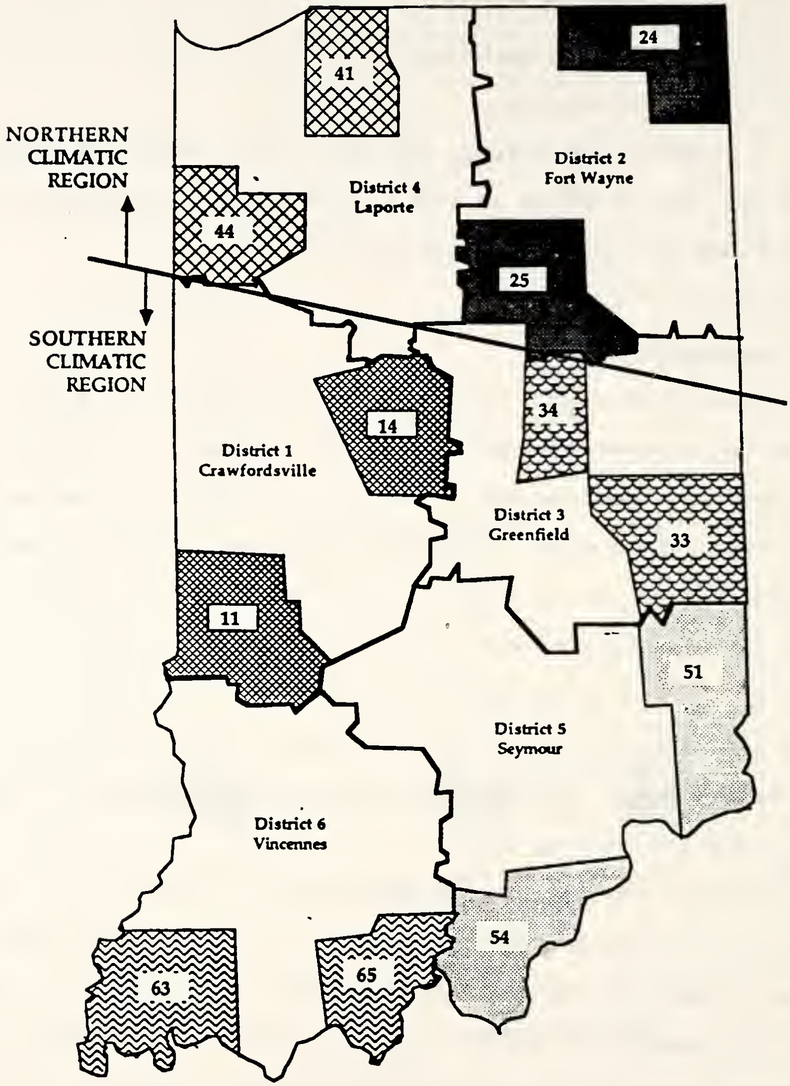


Figure 4.5

Map Illustrating the Location of the Selected Subdistricts

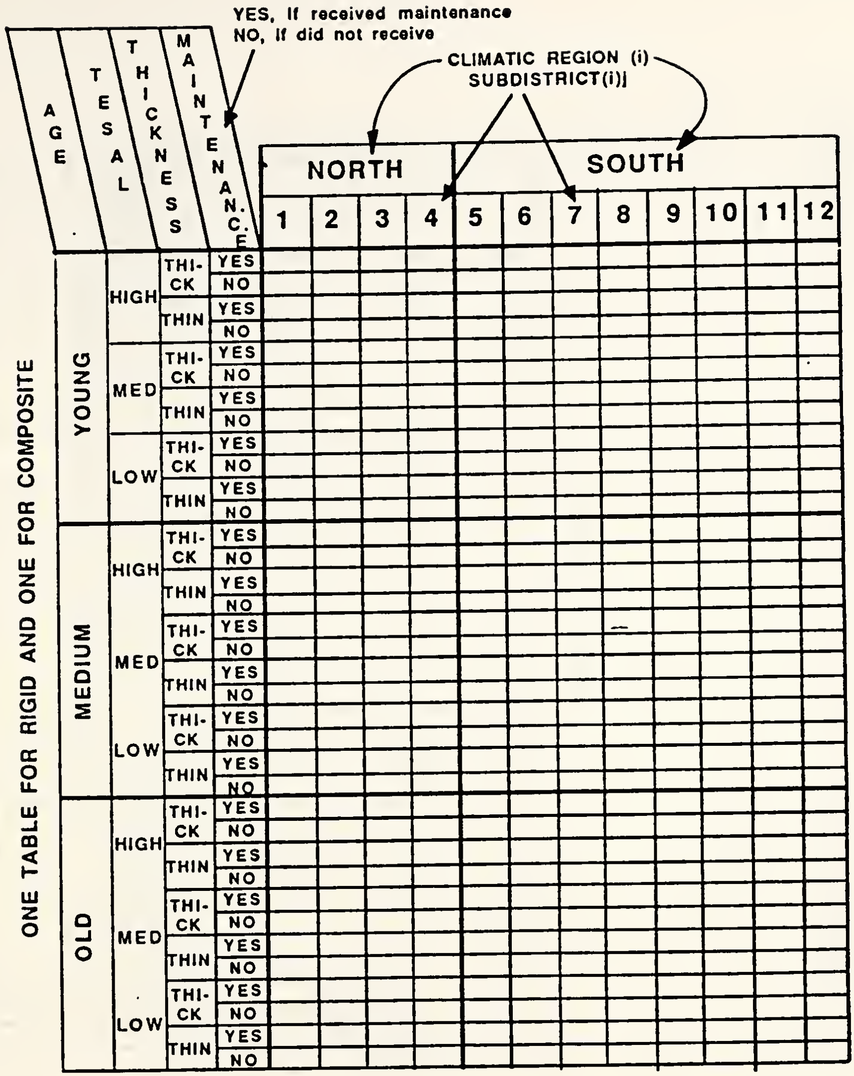


Figure 4.6

The Experiment Design Layout

Table 4.1

Composite Pavement Sample Distribution by Year

SUBDISTRICT	COMPOSITE PAVEMENTS								
	1984			1985			1986		
	IS	OSH	TOTAL	IS	OSH	TOTAL	IS	OSH	TOTAL
24	4	13	17	4	13	17	4	13	17
25	6	13	19	6	13	19	6	13	19
41	-	20	20	-	20	20	-	20	20
44	-	17	17	-	17	17	12	22	34
NORTH. REGION	10	63	73	10	63	73	22	68	90
11	5	31	36	11	31	42	11	32	43
14	7	13	20	9	13	22	9	13	22
33	-	13	13	-	13	13	-	19	19
34	-	6	6	-	6	6	-	6	6
51	12	10	32	12	10	32	12	10	32
54	-	3	3	-	3	3	-	3	3
63	-	15	15	-	15	15	-	15	15
64	-	8	8	-	8	8	-	8	8
SOUTH. REGION	24	99	123	32	99	131	32	106	138
TOTAL STATE	34	162	196	42	162	204	54	174	228

Table 4.2

Rigid Pavement Sample Distribution by Year

SUBDISTRICT	RIGID (PORTLAND CEMENT CONCRETE) PAVEMENTS																										
	PLAIN CONCRETE									REINFORCED									CONTINUOUS REINFORCED								
	IS			OSH			TOTAL			IS			OSH			TOTAL			IS			OSH			TOTAL		
	'84	'85	'86	'84	'85	'86	'84	'85	'86	'84	'85	'86	'84	'85	'86	'84	'85	'86	'84	'85	'86	'84	'85	'86	'84	'85	'86
24	.	.	.	.	.	.	0	0	0	0	0	0	2	2	2	2	2	2	.	.	.	.	.	.	.	.	.
25	.	.	.	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	.	.	.	.	.	.	.	.	.
41	.	.	.	1	1	1	1	1	1	6	6	6	11	11	11	17	17	17	.	.	.	.	.	.	.	.	.
44	.	.	.	.	.	.	.	.	.	12	12	0	10	10	5	22	22	5	2	2	2	.	.	.	2	2	2
NORTH. REGION	.	.	.	10	10	10	10	10	10	18	18	6	23	23	18	41	41	24	2	2	2	.	.	.	2	2	2
11	.	.	.	4	4	3	4	4	3	6	.	.	1	1	1	7	1	1	.	.	.	.	.	.	.	.	.
14	.	.	.	4	4	4	4	4	4	.	.	.	.	.	.	.	.	.	12	10	12	.	.	.	12	10	12
33	.	.	.	9	9	5	9	9	5	.	.	.	7	7	5	7	7	5	.	.	.	.	.	.	.	.	.
34	.	.	.	1	1	1	1	1	1	4	4	4	1	1	1	5	5	5	.	.	.	.	.	.	.	.	.
51	.	.	.	.	.	.	0	0	0	.	.	.	6	6	6	6	6	6	.	.	.	.	.	.	.	.	.
54	4	4	4	2	2	2	6	6	6	10	10	10	5	5	5	15	15	15	.	.	.	.	.	.	.	.	.
63	10	10	10	17	17	17	27	27	27	.	.	.	5	5	5	5	5	5	.	.	.	2	2	2	2	2	2
64	.	.	.	1	1	1	1	1	1	.	.	.	1	1	1	1	1	1	.	.	.	.	.	.	.	.	.
SOUTH. REGION	14	14	14	38	38	33	52	52	47	20	14	14	26	26	24	46	40	38	12	10	12	2	2	2	14	12	14
TOTAL STATE	14	14	14	48	48	43	62	62	57	38	32	20	49	49	42	87	81	62	14	12	14	2	2	2	16	14	16

Table 4.3 Flexible Pavement Sample Distribution
(Fixed for Study Period)

	Flexible Pavements 1984, 1985, 1986		
Subdistrict	ISH	OSH	TOTAL
24	0	65	65
25	0	73	73
41	0	37	37
44	0	44	44
Norther Region	0	219	219
11	0	49	49
14	0	45	45
33	23	146	169
34	26	54	80
51	0	81	81
54	17	58	75
63	15	40	55
65	21	86	107
Southern Region	102	559	
TOTAL STATE	102	778	880

pavement sections received asphalt overlays; consequently, the number of rigid contract sections diminished with time while that of composite contract sections increased.

Table 4.4 shows a similar summary for 1984 but in lane miles. The data shows that a total of 7,448.3 lane-miles were selected, representing about 26% of the total flexible rigid and composite pavements in the State.

4.4 Data Development

The database was developed from many sources of information including routine maintenance records, roughness measurement records, road life records, traffic file and skid resistance file. The data selected can be grouped into seven categories: contract identification information; routine maintenance quantities; maintenance activity unit costs; roughness measurements; pavement surface ratings; skid resistance; and roadway usage. Each of these seven information categories is discussed separately below.

4.4.1 Contract Identification Information

The roughness measurement records are kept by contract. This source also includes information relating to contract length, highway class, highway number, county number, subdistrict and district numbers, surface type, landmarks, number of lanes in each direction, and date of construction or last major maintenance. This information was extracted and added to the newly created roughness file for the study.

4.4.2 Routine Maintenance Quantities

The amount of routine maintenance applied between any two consecutive

Table 4.4

1984 Lane-Miles Sampled

CLASS	CLIMATIC REGION	SUBDISTRICT	RIGID (PORTLAND CEMENT)				COMPOSITE PAVEMENT	FLEXIBLE PAVEMENT	DISTRICT TOTAL	REGIONAL TOTAL	CLASS TOTAL
			PC	RC	CRC	TOT.					
IS	N+S										1536.3
	N									347.0	
		LAPORTE	0	172.6	21.6	194.2	0	0	194.2		
		FORT WAYNE	0	0	0	0	152.8	0	152.8		
	S									1189.3	
		CRAWFORDSVILLE	0	40.60	110.0	150.6	123.2	26.6	300.4		
		GREENFIELD	0	23.6	0	23.6	0	301.5	325.1		
		SEYMOUR	30.4	127.6	0	158.0	119.4	16.6	294.0		
		VINCENNES	99.4	0	0	99.4	0	170.4	269.8		
OSH	N+S										5912.0
	N									1863.6	
		LAPORTE	19.0	188.4	0	207.4	300.7	365.6	873.7		
		FORT WAYNE	90.0	33.4	0	123.4	273.9	592.6	989.9		
	S									4048.4	
		CRAWFORDSVILLE	52.1	14.0	0	66.1	480.4	490.3	1036.8		
		GREENFIELD	77.8	77.0	0	154.8	142.6	732.0	1029.4		
		SEYMOUR	11.4	107.4	0	118.8	194.4	800.0	1113.2		
		VINCENNES	92.0	29.3	16.8	138.1	173.5	557.4	869.0		
BOTH (IS & OSH)	N+S										7448.3
	N									2210.8	
		LAPORTE	19.0	361.4	21.6	401.6	300.7	365.6	1067.9		
		FORT WAYNE	90.0	33.4	0	123.4	426.7	592.6	1142.9		
	S									5237.5	
		CRAWFORDSVILLE	52.1	54.6	110.0	216.7	603.6	516.9	1337.2		
		GREENFIELD	77.8	100.6	0	178.4	142.6	1033.5	1354.5		
		SEYMOUR	41.8	235.0	0	276.8	313.8	816.6	1407.2		
		VINCENNES	191.4	29.3	16.8	237.5	173.5	727.8	1138.8		

roughness measurements was determined from crew day cards obtained from each subdistrict sampled. This task involved scanning literally thousands of such cards in search of the required quantities. Cards with improper identification or missing basic information, such as highway number, county number or location of work were excluded. The relevant information that was extracted from the crew day cards included activity type, date of work, location of work and the number of production units accomplished.

Since between two landmarks more than one contract can exist, the gathered quantities of routine maitenance by activity needed to be reassigned on a contract by contract basis. In order to do that, both the roughness and routine maintenance files had to be matched. Fortunately, both files included many common pieces of highway inventory data; of particular importance was the information relating to highway class and number, county number, subdistrict number and district number. The commonality of this information in both files allowed for redistribution of routine maintenance work to the contract section level.

In order to accomplish the above mentioned task, two location demarkation scales for each highway in each subdistrict were used. The first, a contract section scale, used the identified mileposts for the contract and determined the length of the contract sections in lane-miles. The second, a landmark scale, used mileposts to calculate the distance between two successive landmarks (which could be intersections, bridges, rivers, county lines, etc.). The routine maintenance quantities extracted from the crew day cards were based on the landmark scale. These quantities were redistributed onto the contract sections by proportioning their relative shares according to the ratios of their respective lengths to the length of the landmark section. However, there were cases on Interstate Highways where the location of routine maintenance effort was recorded by mileposts that lay entirely within a contract section; in such cases, the whole amount of routine maintenance was directly assigned to that contract section.

The above task was carried out on a card by card and activity by activity basis. The routine maintenance quantities that were recalculated by contract section were summed betweeen two roughness measurements in order to obtain the total amount of routine maintenance received by the contract section. This quantity was coded into the database.

4.4.3 Routine Maitenance Costs

The quantities of maintenance in the various routine maintenance activities were transformed into a common unit by using maintenance dollars per lane-mile. Since each contract record had its lane-miles reported, to obtain the dollars per lane-mile was a simple operation. Basically, the quantities utilized in a given activity for a given contract were divided by the number of lane-miles of that contract and multiplied by the unit cost of the activity.

The unit prices of the activities were obtained from an earlier study [Sharaf and Sinha 1984]. The unit costs in the earlier study were developed for 1982. The CPI for Operations and Maintenance [FHWA 1988] were used to update these unit costs to 1987. Since the earlier study included only 8 routine maintenance activities of the 14 included in the present study, another source had to be utilized for the development of the remaining six activities. INDOT has Maintenance Management Summary Reports [INDOT 1989] that include estimated amounts of work in each activities and their costs. By dividing the reported total costs by the quantities, the unit costs were developed. Tables 4.5, 4.6 and 4.7 summarize the developed unit costs for rigid, composite, and flexible

Table 4.5

Unit Costs for Rigid Pavement Maintenance Activities.

UNITS IN $/LANE MILE RIGID		ISH UNIT COSTS			OSH UNIT COSTS			TOTAL SYSTEM AVERAGE COSTS
		N	S	STATE AVE.	N	S	STATE AVE.	
Weighting Factor *		0.2258	0.7742	1.0000	0.3364	0.6636	1.0000	0.458128
% of System Ln-ml **		2.1	7.2	9.3	3.7	7.3	11.0	0.541871
PATCHING	Activity 201	160.35	155.10	156.29	122.14	122.14	122.14	137.78
	Activity 202	103.98	82.43	87.30	130.40	130.40	130.40	110.65
	Activity 203	62.90	71.44	69.51	85.64	85.64	85.64	78.25
CRACK SEALING	Activity 206	144.18	175.40	168.35	288.53	288.53	288.53	233.47
	Activity 207	237.46	312.44	295.51	371.52	371.52	371.52	336.70
JOINT SEALING	Activity 209	7.16	5.30	5.72	7.19	7.19	7.19	6.52
	Activity 214	106.57	30.50	47.68	32.90	32.90	32.90	39.67
SEAL COATING	Activity 205	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Activity 208	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SHOULDER ACTIVITIES	Activity 204	133.34	133.34	133.34	133.34	133.34	133.34	133.34
	Activity 210	17.60	17.60	17.60	17.60	17.60	17.60	17.60
	Activity 211	19.35	19.35	19.35	19.35	19.35	19.35	19.35
	Activity 212	256.28	256.28	256.28	256.28	256.28	256.28	256.28
	Activity 213	N/A	N/A	N/A	672.91	672.91	672.91	672.91 ***

* Weighting factors reflection the current sample composition
** Weighting factors used by Sharaf and Sinha [1984] in averaging the statewide unit cost
*** Applies to OSH only

Table 4.6

Unit Costs for Composite Pavement Maintenance Activities

UNITS IN $/LANE MILE COMPOSITE		ISH UNIT COSTS N	ISH UNIT COSTS S	ISH UNIT COSTS STATE AVE.	OSH UNIT COSTS N	OSH UNIT COSTS S	OSH UNIT COSTS STATE AVE.	TOTAL SYSTEM AVERAGE COSTS
Weighting Factor *		0.2000	0.8000	1.0000	0.3417	0.6583	1.0000	0.088607
% of System Ln-mi **		2.1	7.2	9.3	3.7	7.3	11.0	0.911392
PATCHING	Activity 201	144.84	138.48	139.75	108.43	123.56	118.39	, 120.28
	Activity 202	304.53	104.90	144.83	90.46	93.09	92.19	96.86
	Activity 203	105.88	130.76	125.78	124.36	51.33	76.28	80.67
CRACK SEALING	Activity 206	0.00	249.62	199.70	126.92	119.74	122.19	129.06
	Activity 207	204.63	210.65	209.45	379.05	338.80	352.55	3339.87
JOINT SEALING	Activity 209	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Activity 214	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SEAL COATING	Activity 205	1903.06	1903.06	1903.06	1903.06	1903.06	1903.06	1903.06
	Activity 208	1037.61	1037.61	1037.61	1037.61	1037.61	1037.61	1037.61
SHOULDER ACTIVITIES	Activity 204	133.34	133.34	133.34	133.34	133.34	133.34	133.34
	Activity 210	17.60	17.60	17.60	17.60	17.60	17.60	17.60
	Activity 211	19.35	19.35	19.35	19.35	19.35	19.35	19.35
	Activity 212	256.28	256.28	256.28	256.28	256.28	256.28	256.28
	Activity 213	N/A	N/A	N/A	672.91	672.91	672.91	672.91 ***

* Weighting factors reflecting the current sample composition
** Weighting factors used by Sharaf and Sinha [1984] in averaging the statewide unit cost
*** Applies to OSH only

Table 4.7

Unit Costs for Flexible Pavement Maintenance Activities

Activity Code	Production Unit	Unit Cost*
201	Ton of Mix	114.39
202	Ton of Mix	66.63
203	Ton of Mix	46.07
204	Foot-Mile	105.37
205	Lane-Mile	1683.47
206	Linear-Mile	113.97
207	Lane-Mile	305.90
208	Lane-Mile	1200.47**
210	Ton of Agg.	13.91
211	Shoulder-Mile	15.29
212	Shoulder-Mile	202.51
213	Shoulder-Mile	531.45

* All costs are based on 1982 prices.

** Maintenance Management Summary Report [INDOT 1989].

pavements in this study, respectively. This action introduced two minor inconsistencies:

a. while in the earlier study 8 activity unit costs were derived from observing the basic production elements consumed and adding their costs, the newly developed six activity unit costs were derived from aggregate estimates; and

b. the unit costs for the eight activities were stratified by highway class (ISH, OSH), climatic region (N, S), pavement type (Rigid, composite), and by district; the newly developed unit costs for the other six activities, however, could only be stratified by facility type and by climatic region.

4.4.4 Roughness Measurements

Care was taken to gather roughness data from the INDOT adjusted roughness computer files -- not from the raw field data file. Missing information from the file, such as year of reconstruction or overlay, pavement surface type, pavement surface thickness and pavement width was obtained from the Road Life Records.

The roughness data had some shortcomings, including the following:

a. In the case of two-lane, two-way traffic highways, roughness was measured only in one direction for a given year. The same reading was assumed to apply for both directions.

b. Roughness data for some sections displayed an improvement trend in roughness over time, despite the fact that no action was reported to have taken place in between the readings. Some of these were treated as a general measurement error, and others were discarded. This is discussed in more detail in Chapter 5.

c. In some cases, only one reading was taken for sections longer than a mile in length.

d. Although the average period for roughness measurement for the same highway class or pavement type was about one year, the period between some two consecutive roughness measurements for few contract sections varied from 8 to 14 months. Over a longer period of time, this was not considered a serious problem, since measurements were done annually.

4.4.5 Pavement Serviceability Ratings (PSR)

Road Inventory Lists containing these data were obtained from the Program Development Division. The data listings cover the entire highway network (ISH and OSH) and the data are stored by district, county, highway number, direction and classification, using a lankdmark referencing system. For example, a landmark is specified for the beginning of the run (usually county line or a point close to it) and is given the number "0" and PSR ratings are given to sections varying in length, with the intervening landmarks pointed out and their distances from the original landmark reported to the closest one hundredth of a mile. Each assessed section could have a number of landmarks in it. Hence the data needed conversion to the contract section basis used in the present study. In order to do that, the plots of the contract sections on a highway map were matched against the sections in the listings. If a contract section matched or coincided completely within the section in the listing, the PSR value was simply transferred to the contract section; if the contract section did not match or was larger than the PSR section, all related PSR sections were selected and a weighted average by length was computed. The average was then assigned to the contract section. The PSR data had the following limitations:

a. The ratings wère the result of a windshield survey; as súch, they were subjective and not based on instrumental measurements.

b. Most of the readings were done in one direction only; hence the given PSR figures were assumed to apply in both directions. For the cases where both directions were surveyed and reported, there was no need for such assumption.

c. PSR data were available for only 3 of the 4 years covered in the study (1985, 1986 and 1987, but not 1984); hence, in the assessment of this variable, the analysis scope was reduced to two years of maintenance (1985-86 and 1986-87).

d. Discussion with INDOT officials revealed that summer students were often assigned for the collection of this type of data. The use of students with limited experience in roadway condition surveying may have created variations in the ratings from year to year along the same sections.

4.4.6 Skid Resistance Measurements

Skid resistance data were available for the years 1978 until 1989, and filed using contract sections as a referencing system. From 1972 up to and including the year 1982, skid resistance testing was performed on the entire network; however, after 1982, only the Interstate Highways (ISH) were kept on the annual testing program, whereas the Other State Highways (OSH) were put on a 3 year cycle testing scheme. Construction projects complicated the situation for OSH measurements; for example, if a section was scheduled for testing and a bridge somewhere along that section happened to be under rehabilitation or construction, the testing on that section was sometimes cancelled or postponed, thus leaving the section without skid resistance data update for over 3 years.

In the light of the above discussion, the skid resistance data had the following limitations:

a. Since the study period was 1984 to 1987 (that is, after 1982), the usefulness of the data was limited to very few samples from the IS Highways.

b. Since seal coating (the main routine maintenance activity undertaken to improve skid resistance) is generally performed on bituminous surfaces with low volumes of traffic (a condition existing on composite, OSH), the data matched poorly with the sections receiving seal coating.

4.4.7 Roadway Usage

As discussed earlier, the cumulative loading (TESAL) a given pavement has been subjected to since it was last resurfaced affects its performance. In order to calculate the TESAL, an estimate of the total traffic on each pavement section had to be prepared and, then, converted to TESAL. This was accomplished according to the procedure used by Sharaf and Sinha [1984]. The 1978 AADT was available from the roughness file. Traffic figures for two more years were still needed for interpolating for the years in between. The procedure used had 20 year traffic growth factors already established. Those factors were used to develop the 1958 AADT. The 1989 Traffic Statistics Book, published by INDOT, contained last counts for AADT by county. Some had 1984 as last count; others, 1986; and some others 87; and so on. Exponential growth was assumed in between every two AADT values and the traffic estimates for the years in between were developed. The corresponding ESAL were then calculated using conversion factors and percent trucks that were developed by the procedure. The total ESAL was finally calculated by summing up the ESAL values for all the years since last resurfacing.

4.5 Database Development

All of the above data were combined into one computerized database. The data base was subsequently used in the statistical evaluation discussed in the next chapter.

CHAPTER 5

STATISTICAL EVALUATION OF ROUTINE MAINTENANCE EFFECTIVENESS

This chapter presents the summary of results of the statistical evaluation of the first concern of the research, namely whether routine maintenance activities make any difference with respect to pavement performance and, if yes, how much. More detailed results are available in Mouaket [1990] for rigid and composite pavements and in Al-Mansour [1991] for flexible pavements. In keeping with the established framework in Chapter 3, the findings are summarized here under three headings:

1. Testing of data validity;
2. Before/after comparisons; and
3. Quantification of relationships.

5.1 Testing of Data Validity

The application of the various validity checks mentioned in Chapter 3 earlier resulted in the detection of three main problems.

5.1.1 Section Misfits

The scatter plots of maintenance cost versus age and cumulative equivalent single axle loads (TESAL) for the three design types of rigid pavements (JPCP, JRCP, CRCP) were analysed and evaluated. The plots for JPCP and JRCP revealed a reasonable trend, but that of CRCP did not. In fact an inverse relationship between maintenance cost and age was obtained as illustrated in Figure 5.1. This declining trend does not make much engineering sense because as the road becomes older, one would expect it to require more care, not less. An

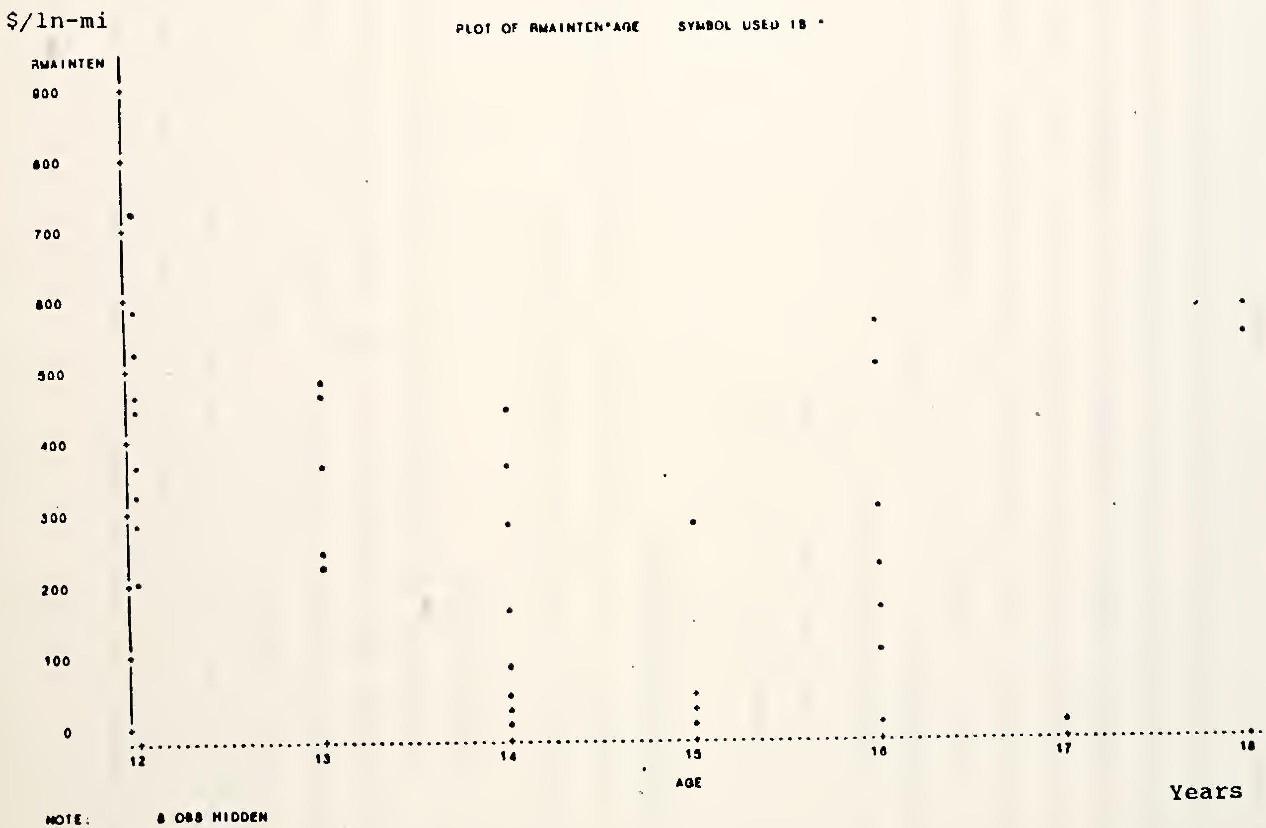


Figure 5.1

Scatter Plot of Low Order Maintenance Against Age for CRCP Pavement evaluation of the potential reasons for such behavior indicated that the pattern was the result of existing practices at INDOT. In CRC pavements, dense cracking is normal. Such pavements tend to have short transverse cracking spacings and develop cracks in clusters. Consequently, it can develop short waves or undulation as a result of poor support conditions, frost and heave, or permanent deformation of subgrade. INDOT's existing practice favors the upkeeping of this type of pavement by applying thick overlays and not routine maintenance or thin overlays. The explanation for the existing inverse trend of maintenance costs versus age is that maintenance is contracted out and hence excluded from the routine maintenance expenditures. Since routine maintenance activities are not captured in the process of collecting data, this pavement type was excluded from the evaluation.

5.1.2 Poor Reporting of Maintenance Data

The datafiles for flexible, rigid and composite pavements were sorted and the sections receiving zero maintenance were printed out. This group of sections was important because it was the pool from which various control groups were selected for the various significance tests. A number of serious problems were observed. Firstly, a relatively low number of sections were obtained for rigid (45 sections) and for composite (28 sections) pavements. For flexible, this was not an issue (107 sections). The low numbers obtained for rigid and composite can be explained in terms of the relatively long life of rigid and composite pavements (that is, the chances that an old pavement will not need any maintenance are very low) and the fact that very little rigid pavement building activity has taken place in the last decade. Secondly, the situation was complicated further by the fact that 26 sections of the zero maintenance rigid pavement group and 13 of that of composite displayed improvements in their surface condition, contrary to the logical expectation of at least holding their condition at the same level or deteriorating without any maintenance. Twenty two sections of flexible pavements displayed similar behavior. The observed improvement in condition was sometimes in roughness; at other times, in pavement surface ratings; and at some other times, in both. For example, 12 rigid and 5 composite sections displayed less than 150 points improvement in roughness; 9 rigid and 4 composite, between 150 and 800 points; and 5 rigid and 4 composite, greater than 800 points. Each of these groups was treated separately. The improvement of 150 points in the first group was treated as measurement variation error, consistent with INDOT's experience with the equipment calibration error of 10% and up to 150 points as maximum. The records of these sections were included in the data bank but with zero improvement in the condition. The records of the sections in the third group (improving more than 800 points) were checked against the original INDOT records and were found to have been overlaid. They were eliminated from the datafile since their improvement was not related to routine maintenance at all. The second group (improving 150 to 800 points) was reviewed with INDOT staff, and the conclusion was that these sections must have received some form of maintenance which was not reported or recorded. To demonstrate this reasoning, consider the case when both roughness and pavement surface rating improved, activities like patching or seal coating must have been applied. If, however, PSR improved but RN deteriorated, patching or crack sealing could have been applied because both activities affect PSR but not necessarily the RN; and so on. The final decision was to eliminate these sections from the datafile because, most likely, they were not zero maintenance sections.

After the cleanup, only 31 rigid pavement sections and 20 composite were left as control groups receiving zero maintenance. Eighty five sections of flexible pavement were left as a control group.

5.1.3 Inadequate Skid Resistance Measurements

Of all the 14 routine maintenance activities, perhaps the one that affects skid resistance most is seal coating. In Indiana, seal coating is carried out only on composite and flexible pavements carrying low volumes of traffic (i.e., other state highways -- not interstate). As confirmed by INDOT staff and as manifested in the data base, the department's skid resistance measurement program ensures good coverage of the interstate system; measurements, except for some odd cases, was available almost on an annual basis. For other state highways (OSH), however, the coverage was at a lower rate; complete measurement coverage was set on a three year cycle. Investigation of the data revealed that gaps of more than three years also existed. The reason for such extended gaps is that when maintenance or capital work activities (such as construction, bridge deck repairs, patching, crack sealing) are taking place at the time when the crews are scheduled to take measurements, the measurement is postponed for fear of creating conflict.

When the INDOT's skid resistance data were matched with the study sample records, very poor matching results were obtained, but the most crucial of which was in the sections receiving seal coating. To illustrate, none of the 22 sections of composite pavement in the one-year datafile that received seal coating had both of the "before" and "after" measurements available. These measurements are essential for the calculation of group means and the testing of significance. In the case of the three-year datafile, only one section had the "before" and "after" skid numbers available.

Given this situation, it was concluded that a meaningful evaluation of the effectiveness of seal coating (or any other activity for that matter) in terms of improving skid resistance was not possible. Hence, skid resistance was dropped as a candidate indicator for condition to be evaluated in this study. This should not be construed to imply that skid resistance is not a valid indicator of maintenance effectiveness, but that its elimination from the study was due to the absence of adequate data.

5.1.4 Aggregation of Maintenance Data

Part of this study was to investigate if maintenance relationships are more stable when developed over a multi-year aggregated data base than when developed over one year periods. The maintenance data for the years 1984, 1985 and 1986 were summed to form the 1984-1986 maintenance effort and the roughness and pavement surface ratings for 1984 and 1987 were used as the before and after measurements, respectively. Only sections that did not have any changes in surface type (i.e., ones that are consistent in age and thickness) were included. The resulting 3-year datafile were extremely small, particularly in relation to the control groups. To demonstrate, the 3-year rigid datafile included 132 sections in total and that of the composite, 171. However, the addition of the maintenance activities for the three years reduced the control groups (i.e., zero maintenance) in both rigid and composite pavements to 2 sections for composite and 1 section for rigid. Without a reasonably sized control group, meaningful comparisons could not be made. Consequently, the three year data base for flexible, rigid and composite pavements were considered unsuitable for this evaluation.

In closure, taking all the above decisions into consideration, testing was confined to the one year datafiles, where flexible pavement, composite pavement, and JPCP and JRCP designs of the rigid pavement were included. Only two condition indicators were investigated: roughness number (RN) and pavement serviceability rating (PSR).

5.2 Before/After Comparisons

The before/after comparisons were separately carried out for rigid, composite and flexible pavements, and the results are documented below.

5.2.1 Rigid Pavement

Statistical tests for the impact of various activity combinations on roughness number (RN) and pavement surface rating (PSR) were carried out. A detailed discussion of the results and their interpretation can be found in Mouaket [1990]. Following is a summary of the findings.

5.2.1.1 Activities Impacting RN

Table 5.1 summarizes the results obtained from this test. Of the four groups of activities related to rigid pavements, sections receiving only patching were found to have an evidence of a definitely significant impact of such activity on roughness. Sections receiving patching and crack sealing or patching and joint sealing provided evidence of marginal significance of such activities on roughness. Sections receiving crack sealing and shoulder activities combined demonstrated a significant impact on their roughness as a result of this maintenance. All other sections receiving other groupings of activities did not

Table 5.1

Summary of Before/After Tests of Rigid Pavements Using Roughness Measurements

Rigid Pavement Activities Tested	Overall Model Statistics						Independent Variable Statistics		
	No. of Observ.	Model df	Error df	R^2	R^2 Adjusted	P > F	Significant Variables	P > F	Type of Significance
Patching	143	51	91	0.7112	0.5498	0.0001	Test*Maint*Class*Lacation	0.0002	Definite
Crack Sealing	65	34	31	0.9358	0.8631	0.0001	NONE	--	--
Joint Sealing	50	23	26	0.9299	0.8681	0.0001	NONE	--	--
Shoulder	86	33	52	0.8825	0.8080	0.0001	NONE	--	--
Patching + Crack Sealing	194	49	144	0.5616	0.4124	0.0001	Test*Maint*Lacation	0.0662	Marginal
Patching + Joint Sealing	56	25	30	0.9082	0.8316	0.0001	Test*Maint	0.0847	Marginal
Patching + Shoulder	179	49	129	0.4915	0.2983	0.0001	NONE	--	--
Crack Sealing + Joint Sealing	48	21	26	0.9172	0.8506	0.0001	NONE	--	--
Crack Sealing + Shoulder	70	23	46	0.8858	0.8287	0.0001	Test*Maint	0.0163	Definite
Joint Sealing + Shoulder	60	27	32	0.9244	0.8606	0.0001	NONE	--	--

Table 5.1 . . . Continued

Rigid Pavement Activities Tested	Overall Model Statistics						Independent Variable Statistics		
	No. of Observ.	Model df	Error df	R^2	R^2 Adjusted	P > F	Significant Variables	P > F	Type of Significance
Patching + Crack Sealing + Joint Sealing	57	25	31	0.8842	0.7911	0.0001	NONE	--	--
Patching + Crack Sealing + Shoulder	168	46	121	0.5889	0.4328	0.0001	NONE	--	--
Patching + Joint Sealing + Shoulder	98	35	62	0.5874	0.3545	0.0007	NONE	--	--
Crack Sealing + Joint Sealing + Shoulder	46	19	26	0.9153	0.8534	0.0001	NONE	--	--
All Activities Togther	79	37	41	0.6940	0.4179	0.0023	NONE	--	--

yield any evidence of significance.

5.2.1.2 Activities Impacting PSR

Table 5.2 summarizes the results obtained from this test. Evidence of definite significance of the impacts of maintenance activities on pavement serviceability ratings were obtained in the circumstance where sections received patching only, crack sealing only, or shoulder activities. In the circumstance where combinations of activities were applied, sections receiving patching and crack sealing, or patching and shoulder activities, or crack sealing and shoulder activities, have provided evidence of definite significance.

5.2.2 Composite Pavement

Statistical tests for the impact of various activity combinations on roughness number (RN) and pavement serviceability rating (PSR) were carried out. A detailed discussion of the results and their interpretation can be found in Mouaket [1990]. Following is a summary of the findings.

5.2.2.1 Activities Impacting RN

Table 5.3 summarizes the results obtained from this test. Definite significance of impact on roughness was obtained in the case of sections receiving: crack sealing only; shoulder activities only; or patching and crack sealing. Marginal significance was obtained in the case of sections receiving patching only.

5.2.2.2 Activities Impacting PSR

Table 5.4 summarizes the results obtained for this test. It is obvious in the summaries that the r-squared and the adjusted r-squared values were much lower for composite pavements than those for rigid. This can imply one

Table 5.2

Summary of Before/After Tests of Rigid Pavements Using Pavement Serviceability Ratings

Rigid Pavement Activities Tested	Overall Model Statistics						Independent Variable Statistics		
	No. of Observ.	Model df	Error df	R^2	R^2 Adjusted	P > F	Significant Variables	P > F	Type of Significance
Patching	98	43	54	0.8924	0.8074	0.0001	Test*Maint Test*Maint*Design Type Test*Maint*Class*Lacation Test*Main*Lacation	0.0297 0.0070 0.0036 0.0504	Definite Definite Definite Marginal
Crack Sealing	42	23	18	0.9505	0.8874	0.0001	Test*Maint	0.0320	Definite
Joint Sealing	38	21	16	0.9619	0.9118	0.0001	NONE	--	--
Shoulder	62	31	30	0.9617	0.9220	0.0001	Test*Maint	0.0052	Definite
Patching + Crack Sealing	102	45	56	0.8548	0.7384	0.0001	Test*Maint Test*Maint*Class*Location	0.0093 0.0004	Definite Definite
Patching + Joint Sealing	42	21	20	0.9601	0.9187	0.0001	NONE	--	--
Patching + Shoulder	128	43	84	0.5775	0.3611	0.0001	Test*Maint*Design Type	0.0221	Definite
Crack Sealing + Joint Sealing	36	19	16	0.9579	0.9079	0.0001	NONE	--	--
Crack Sealing + Shoulder	54	19	34	0.9453	0.9160	0.0001	Test*Maint	0.0007	Definite
Joint Sealing + Shoulder	48	25	22	0.9572	0.9085	0.0001	NONE	--	--

Table 5.2 . . . . Continued

Rigid Pavement Activities Tested	Overall Model Statistics						Independent Variable Statistics		
	No. of Observ.	Model df	Error df	R^2	R^2 Adjusted	P > F	Significant Variables	P > F	Type of Significance
Patching + Crack Sealing + Joint Sealing	46	23	22	0.9493	0.8964	0.0001	NONE	-	-
Patching + Crack Sealing + Shoulder	114	39	74	0.5426	0.3016	0.0013	NONE	-	-
Patching + Joint Sealing + Shoulder	66	29	36	0.7971	0.6340	0.0001	NONE	-	-
Crack Sealing + Joint Sealing + Shoulder	34	17	16	0.9469	0.8903	0.0001	NONE	-	-
All Activities Togther	58	33	24	0.8837	0.7240	0.0001	Test*Maint*Loading	0.0039	Definite

Table 5.3

Summary of Before/After Tests of Composite Pavements
Using Roughness Measurements

Composite Pavement Activities Tested	Overall Model Statistics						Independent Variable Statistics		
	No. of Observ.	Model df	Error df	R^2	R^2 Adjusted	P > F	Significant Variables	P > F	Type of Significance
Patching	232	44	187	0.4471	0.3171	0.0001	Test*Maint*Class*Location	0.0884	Marginal
Crack Sealing	80	32	47	0.5974	0.3233	0.0074	Test*Maint*Age	0.0411	Definite
Seal Coating	44	17	26	0.6104	0.3557	0.0218	NONE	--	--
Shoulder	89	33	55	0.7464	0.5942	0.0001	Test*Maint Test*Maint*Class Test*Maint*Thickness Test*Main*Loading	0.0221 0.0010 0.0097 0.0189	Definite Definite Definite Definite
Patching + Crack Sealing	241	44	196	0.4314	0.3038	0.0001	Test*Maint Test*Maint*Age	0.0105 0.0108	Definite Definite
Patching + Seal Coating	49	20	28	0.7734	0.6116	0.0001	NONE	--	--
Patching + Shoulder	238	40	197	0.3241	0.1869	0.0001	NONE	--	--
Crack Sealing + Seal Coating	42	16	26	0.5989	0.3514	0.0215	NONE	--	--
Crack Sealing + Shoulder	70	31	38	0.6409	0.3484	0.0112	NONE	--	--
Seal Coating + Shoulder	43	16	26	0.5990	0.3528	0.0215	NONE	--	--

Table 5.3 . . . . Continued

Composite Pavement Activities Tested	Overall Model Statistics						Independent Variable Statistics		
	No. of Observ.	Model df	Error df	R^2	R^2 Adjusted	P > F	Significant Variables	P > F	Type of Significance
Patching + Crack Sealing + Seal Coating	45	18	26	0.6408	0.3921	0.0137	NONE	-	-
Patching + Crack Sealing + Shoulder	236	42	193	0.3560	0.2159	0.0001	NONE	-	-
Patching + Seal Coating + Shoulder	56	26	29	0.7287	0.4854	0.0025	NONE	-	-
Crack Sealing + Seal Coating + Shoulder	43	16	26	0.5990	0.3522	0.0215	NONE	-	-
All Activities Togther	53	24	28	0.8712	0.7609	0.0001	Test*Maint Test*Maint*Location	0.0958 0.0016	Marginal Definite

Table 5.4

Summary of Before/After Tests of Composite Pavements Using Pavement Serviceability Ratings

Composite Pavement Activities Tested	Overall Model Statistics						Independent Variable Statistics		
	No. of Observ.	Model df	Error df	R^2	R^2 Adjusted	P > F	Significant Variables	P > F	Type of Significance
Patching	178	41	136	0.3153	0.1090	0.0374	NONE	--	--
Crack Sealing	68	31	36	0.5083	0.0850	0.2970	NONE	--	--
Seal Coating	42	17	24	0.4516	0.0633	0.3599	NONE	--	--
Shoulder	88	33	54	0.4443	0.1046	0.1872	NONE	--	--
Patching + Crack Sealing	148	41	106	0.3954	0.1616	0.0170	NONE	--	--
Patching + Seal Coating	44	17	26	0.5020	0.1764	0.1558	NONE	--	--
Patching + Shoulder	158	39	118	0.2408	0.0000	0.5446	NONE	--	--
Crack Sealing + Seal Coating	40	15	24	0.4213	0.0600	0.3590	NONE	--	--
Crack Sealing + Shoulder	66	29	36	0.5276	0.1473	0.1750	NONE	--	--
Seal Coating + Shoulder	40	15	24	0.4213	0.0600	0.3590	NONE	--	--

Table 5.4. Continued.

Composite Pavement Activities Tested	Overall Model Statistics						Independent Variable Statistics		
	No. of Observ.	Model df	Error df	R^2	R^2 Adjusted	P > F	Significant Variables	P > F	Type of Significance
Patching + Crack Sealing + Seal Coating	40	15	24	0.4213	0.0600	0.3590	NONE	-	-
Patching + Crack Sealing + Shoulder	180	37	142	0.3687	0.2043	0.0004	Test*Maint*Location	0.0157	Definite
Patching + Seal Coating + Shoulder	48	23	24	0.4956	0.0124	0.4751	NONE	-	-
Crack Sealing + Seal Coating + Shoulder	40	15	24	0.4213	0.0600	0.3591	NONE	-	-
All Activities Togther	46	21	24	0.5107	0.0827	0.3362	NONE	-	-

of two conditions: either the quality of the composite data was poorer or additional variables are needed to explain the variation in the PSR measurements. The preliminary testing of the data indicated that both conditions are relevant to the existing database. To illustrate, the performance of the overlay in composite pavements can be expected to vary with the type of concrete slab underneath (i.e., JPCP or JRCP), but the concrete slab type information was not reliably available and was not included in the database. Its exclusion from the analysis (along with other variables such as the quality of drainage) could be a contributing factor. The other contributing factor can be illustrated by the fact that plots of the PSR measurements against age and cumulative ESAL resulted in less pronounced trends than those for rigid pavement. This implies that the data variation was wider and hence the poorer r-squared values.

Evidence of definite significance was obtained in the case of sections receiving patching, crack sealing and seal coating combined. No other evidence of any kind was obtained.

It is noteworthy that the r-squared values and the adjusted r-squared values were measurably higher for roughness tests than for PSR tests. This suggests that the selected independent variables explained the variation of roughness data better than the PSR data for this type of pavement.

5.2.3 Flexible Pavement

Statistical tests for the impact of various activity combinations on roughness number (RN) and pavement serviceability rating (PSR) were carried out. A detailed discussion of the results and their interpretation can be found in

Al-Mansour [1991]. Following is a summary of the findings.

5.2.3.1 Activities Impacting RN

In the area of flexible pavements, it was possible to carry out this test by highway class. Testing was done using the 9 groupings mentioned earlier in this report. Tables 5.5 and 5.6 summarize the results obtained from this test for OSH and ISH, respectively.

For OSH, definite significance of impact on roughness was obtained for all groups of sections immaterial of which of the nine activities they received. In other words, no matter what group of maintenance activity was applied, significant impacts on roughness were obtained. However, for ISH, significant impact on roughness was detected only in the case where sections received basic routine maintenance.

5.2.3.2 Activities Impacting PSR

Tables 5.7 and 5.8 summarize the results obtained from this test for OSH and ISH, respectively. For OSH, definite significance of impact on roughness was obtained for sections receiving basic routine maintenane; basic routine maintenance and chip seals; basic routine maintenance and sand seals; basic routine maintenance and shoulder activities; as well as basic routine maintenance and sand seals and shoulder activities. Marginal impacts were detected for sections receiving shoulder activities; basic routine maintenance and chip seals and shoulder activities; as well as basic routine maintenance and premix leveling and shoulder activities. As for ISH, only marginal significant impact was detected in the case where sections received basic routine maintenance.

Table 5.5

Effect of Flexible Pavement Maintenance on Change in Pavement Roughness (OSH)

Maintenance Activities Tested	Overall Model Statistics						Independent Variable Statistcs		
	No. of Observ.	Model df	Error df	R^2	Adj. R^2	P>F	Significant Variables	P>F	Type of Significance
BRM*	294	74	219	0.4879	0.3917	0.0271	Maint Maint*Dist Maint*Age	0.0093 0.0087 0.0237	Definite Definite Definite
BRM. + Chip Sealing	64	24	39	0.5162	0.4121	0.0011	Maint*Dist Maint*Age	0.0056 0.0015	Definite Definite
BRM. + Sand Sealing	66	26	39	0.3394	0.2831	0.0361	Maint Maint*Dist Maint*Age	0.0270 0.0543 0.0164	Definite Marginal Definite
BRM. + Premix Leveling	71	30	40	0.4311	0.2024	0.0093	Maint*Age Maint*Traffic	0.0248 0.0177	Definite Definite
Shoulder Activities	121	47	73	0.4798	0.3971	0.0013	Maint Maint*Dist*Age Maint*Dist*Traffic Maint*Age*Traffic	0.0245 0.0130 0.0701 0.0445	Definite Definite Marginal Definite
BRM. + Shoulder	451	75	371	0.4185	0.3784	0.0143	Maint*Age Maint*Dist*Age	0.0111 0.0001	Definite Definite
BRM + Chip Sealing + Shoulder	46	20	25	0.5078	0.3824	0.0073	Maint*Dist Maint*Age	0.0072 0.0158	Definite Definite
BRM + Sand Sealing + Shoulder	16	10	5	0.6037	0.3072	0.0167	Maint*Dist	0.0217	Definite
BRM + Premix Leveling + Shoulder	24	12	11	0.4807	0.2103	0.0118	Maint*Dist	0.0327	Definite

* Basic Routine Maintenance (Patching and Crack Sealing)

Table 5.6

Effect of Flexible Pavement Maintenance on Change in Pavement Roughness (ISH)

Maintenance Activities Tested	Overall Model Statistics						Independent Variable Statistcs		
	No. of Observ.	Model df	Error df	R^2	Adj. R^2	P>F	Significant Variables	P>F	Type of Significance
BRM*	78	12	66	0.3716	0.1792	0.0068	Maint Maint*Dist	0.0361 0.0127	Definite Definite
Shoulder	25	9	16	0.3924	0.2312	0.0451	None	-	-
BRM + Shoulder	37	8	29	0.4260	0.2160	0.0352	None	-	-

* Basic Routine Maintenance (Patching and Crack Sealing)

Table 5.7

Effect of Flexible Pavement Maintenance on Change in Pavement Serviceability (OSH)

Maintenance Activities Tested	Overall Model Statistics						Independent Variable Statistcs		
	No. of Observ.	Model df	Error df	R^2	Adj. R^2	P>F	Significant Variables	P>F	Type of Significance
BRM*	196	61	134	0.3295	0.2842	0.0453	Maint Maint*Dist	0.0372 0.0871	Definite Marginal
BRM. + Chip Sealing	49	19	29	0.3738	0.1627	0.0247	Maint*Age	0.0386	Definite
BRM. + Sand Sealing	52	22	29	0.3931	0.1585	0.0144	Maint*Age	0.0450	Definite
BRM. + Premix Leveling	54	24	29	0.3826	0.0921	0.0374	None	-	-
Shoulder Activities	90	38	51	0.5641	0.3394	0.0329	Maint*Dist*Age	0.0653	Marginal
BRM. + Shoulder	288	66	221	0.2314	0.1332	0.0104	Maint*Dist Maint*Age	0.0351 0.0010	Definite Definite
BRM + Chip Sealing + Shoulder	31	14	16	0.5481	0.3456	0.0439	Maint*Dist	0.0658	Marginal
BRM + Sand Sealing + Shoulder	10	6	3	0.4093	0.2184	0.0454	Maint Maint*Age	0.0348 0.0889	Definite Marginal
BRM + Premix Leveling + Shoulder	18	9	8	0.3133	0.0437	0.2034	Maint*Dist	0.0583	Marginal

* Basic Routine Maintenance (Patching and Crack Sealing)

Table 5.8

Effect of Flexible Pavement Maintenance on Change in Pavement Serviceability (ISH)

Maintenance Activities Tested	Overall Model Statistics						Independent Variable Statistcs		
	No. of Observ.	Model df	Error df	R^2	Adj. R^2	P>F	Significant Variables	P>F	Type of Significance
BRM*	43	9	34	0.2817	0.0653	0.0231	Maint*Dist	0.0823	Marginal
Shoulder	13	5	7	0.8245	0.6873	0.0141	None	-	-
BRM + Shoulder	28	18	27	0.4074	0.2451	0.0287	None	-	-

* Basic Routine Maintenance(Patching and Crack Sealing)

5.3 Quantification of Relationships

A part of this research was devoted to determine the relative performance of the following parameters in representing the impact of routine maintenance on pavement condition: roughness and PSR; the incremental change in roughness and PSR; and the per cent change in roughness and PSR. In order to make this assessment, relationships among the relevant variables had to be developed and compared. The flexibility of the Generalized Linear Model (GLM) in treating continuous and class variables in one mathematical operation made the technique attractive for this task. This analysis was performed by pavement type and following is a summary of findings.

5.3.1 Rigid and Composite Pavements

A first step towards quantification was to test the data for normality, constancy of error variance and other assumptions underlying linear regression techniques. The normality tests indicated that the incremental and percent change did not have normal populations, even with various complex transformations. The decision was then made that PSR and RN were the best dependent variables to use, not the incremental rate or the percent rate of change.

The quantification of the relationships among PSR or RN, on the one hand, and the pavement attributes, on the other, was carried out by pavement type using two different approaches: one approach was a stratification by pavement and maintenance types and the calibration of performance models relating the performance indicators to the pavement attributtes; and the other, the stratification of data by policy variables and developing performance equations relating the performance indicators to the other pavement attributes.

To illustrate the two methods, in the first approach, the sections were stratified by pavement type (rigid or composite) and by maintenance type. For each combination of maintenance category and surface type (seven in total), two models were calibrated: one relating the PSR to the attributes of the sections and the other, relating RN to the attributes. These models took the general forms shown below:

RN (group x) = f(class + location + thickness + age + loading + design type + climate); and

PSR (group x)= f(class + location + thickness + age + loading + design type + climate).

Detailed results of this approach are available in Mouaket [1990]; few observations, however, can be made:

- As more routine maintenance activities were introduced into the analysis, the r-squared value dropped. This was explainable by the fact that the effectiveness of maintenance is sensitive to the type and extent of distress experienced by the pavement at the time of treatment application. Since more treatments indicate more intense distress, the variance in the effectiveness of the treatment would be high. For example, seal coating is not expected to arrest fatigue cracking because such distress in the pavement is due to the pavement weakness in carrying the type of loading being applied; consequently, even after seal coating, it will continue to crack at other spots. Seal coating, however, could effectively deal with shrinkage cracking, because once the pavement cracks to adjust for its expansion and contraction needs, it is unlikely that such cracking will repeat. The reported PSR or RN by field surveys summarize the condition of cracking in general, but not necessarily the condition of the same cracks. Such a measure is like the temperature of the human body: a summary indicator of trouble, but not the trouble itself. The data are not detailed enough to enable their stratification and analysis by distress type.

- The low r-squared values obtained for rigid pavements suggest that all the select variables can explain only a relatively small portion of the variation. The high F-values and the extremely low P>F indicates that the relationships are significant for whatever portion of variance that the relationships can explain. To illustrate, the relationship for predicting PSR in terms of location and age for low order maintenance can explain only 54.5% of the variance; the high F-value of 11.08 and P>F= 0.0001 suggest that the relationship is significant because such F-value is not likely to be exceeded if another experiment is repeated.
- The r-squared values obtained for composite pavements are far lower than those obtained for rigid, for all groups. Again this indicates that there may be a need to include other variables for composite than for rigid. The F-values are also lower which suggest that the quality of data is not as good as for rigid.

In the second approach, stratification by policy variables, the data were first stratified by surface type (rigid or composite), by class (ISH or OSH), by climatic region (North or South), and for rigid pavement only by design type (plain or reinforced). Age, loading, maintenace and thickness were left as continuous independent variables to explain the variation in the RN and PSR data. The models used were of the following general type:

PSR (for a given stratification) = f(Age (P) + Loading (Q)

or RN (for a given stratification) + Maintenance + Total Thickness (R))

A number of observations can be stated in relation to the obtained results:

- For plain rigid pavements a good relationship existed for the ISH located in the southern climatic region. For that group of highways, it was possible to explain over 90% of the variation in the PSR data using the above mentioned variables; only age, load and maintenance could explain significant portions of the PSR data variation.
- for plain concrete pavements, a reasonable relationship existed between roughness and the four independent variables, with age and load playing a significant role in explaining the variation in the RN data. Over 55% of the variation in RN data was explainable in this relationship.
- although a strong relationship was spotted between RN and the independent variables for OSH in the Northern climatic region, thickness could marginally explain some of the variation in the RN data.
- for reinforced concrete pavements, strong relationships existed in the case of ISH in both Northern and Southern climatic regions, with the stronger relationship in the latter. In the Northern region, age and maintenance could explain significant portions of the variation in the PSR data whereas in the south, age, load and maintenance did. For OSH, the relationship in the North was marginally significant and in the South, not significant at all.
- reasonable relationships between ISH roughness and maintenance and marginal relationships between RN and Loading exist only in the northern climatic region. For OSH, no strong relationships could be detected.
- no strong or even reasonable relationships exist for either ISH or OSH. Again the absence of some key variables or perhaps the quality of the composite pavement data could be the reason underlying such performance.

To recoup the above discussion, both approaches illustrated that only few strong relationships in the area of rigid pavement, particularily relating to ISH, can be calibrated. The composite data proved to be confounded in the sense that five or more interaction variables had to be included before any reasonable levels of r-squared could be reached. If these relationships are to be used for forecasting impacts or performance, such high levels of interactions are not operationally meaningful. A comparison of the two methods indicates two important conclusions:

a. The approach of stratifying by the policy variables would probably produce more useful results in future research than the first approach where roadways are stratified by maintenance level; and

b. Since, in practice, each distressed road receives adequate maintenance to keep it protected from early deterioration (assuming availability of required resources) and not according to a predetermined schedule of maitenance, the use of the second approach would be more operational. The concept of "level of maintenance" a given section receives is meaningful only with the benefit of hindsight.

5.3.2 Flexible Pavements

The adequacy of the available flexible pavement data and its reasonable distribution accross the cells of the design have resulted in the successful development of some performance curves. Separate pavement condition prediction models for groups of sections, each receiving a certain maintenance category, were developed.

Maintenance Effect Models:

For modeling the effect of maintenance, the pavement sections were sorted by highway class into Interstate and Other State highway sections and then grouped by maintenance activity received during the analysis period. Two models were developed for each combination: one model related the effect of maintenance to pavement roughness, and the other, effect of maintenance to pavement serviceability ratings. The regression models took the following forms:

RN(Maint.i) = a + b*Age + c*ESAL + d*Region + E

PSR(Maint.i) = a + b*Age + c*ESAL + d*Region + E

where,

RN = pavement roughness measurements (counts/mile)

PSR = pavement serviceability ratings

Maint.i = maintenance cost in category i

Age = pavement age since construction or last resurfacing (in years)

ESAL = mean annual equivalent single axle loads (in thousands)

Region = dummy variable representing the effect of climatic region in which pavement contract section is located: (applies for OSH only), 0 for northern region, and 1 for southern region

a,b,c,d = regression coefficients

E = error term

In order to meet the basic regression assumptions (namely, constancy of variance of the regression residuals and the normality of the residuals' distribution) a logarithmic transformation of pavement roughness was essential. The regression parameters were estimated using the multiple linear regression analysis procedure of the SAS package and the results are available in Al-Mansour [1991].

The developed equations estimate the envelope of all points which represent sections that have received a given maintenance group of activities at various age groups. These envelopes do not estimate the service life of the various maintenance strategies because their calibration assumes that the maintenance activity is repeated annually, that is, at every year in the life of the pavement -- a situation which is not likely to occur. The curves in this case, however, can still be used to illustrate the relative effect of various higher order routine maintenance strategies. The above referred equations are graphically presented in Figures 5.2 to 5.7. These plots do not illustrate any appreciable difference among the various lower order routine maintenance activity groups and, consistent with intuitive and engineering expectations, the more intensive higher order maintenance yielded the more significant impacts.

5.4 Summary and Conclusions

The statistical analysis indicated that the quality of available data deteriorated from flexible pavement, to rigid pavement, and from rigid, to composite. Consequently, firm conclusions could be derived mainly for the effectiveness of flexible and rigid pavement routine maintenance.

The analysis of rigid and composite pavement maintenance effectiveness was hampered by a number of problems related primarily to the availability and quality of data. In some cases, information regarding certain factors such as drainage, design type or type of distress, was not available; in other cases, the

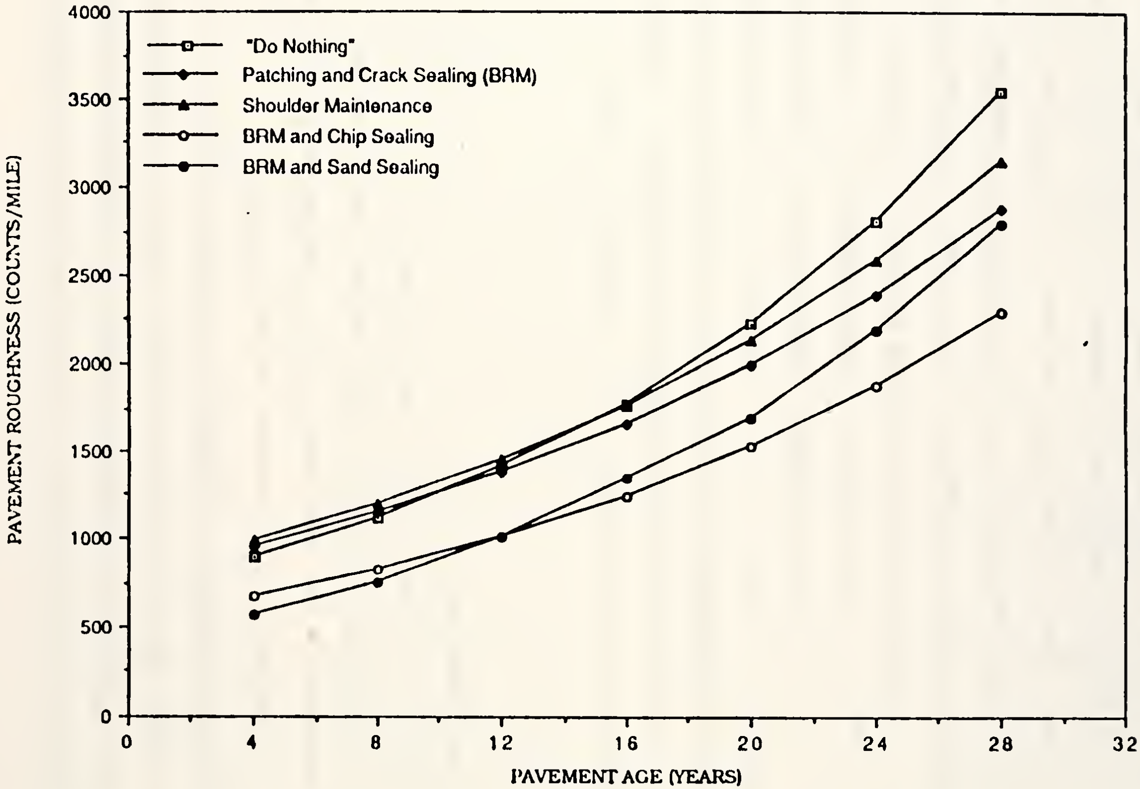


Figure 5.2

Effect of Maintenance Categories on Pavement Roughness in the Northern Region (OSH)

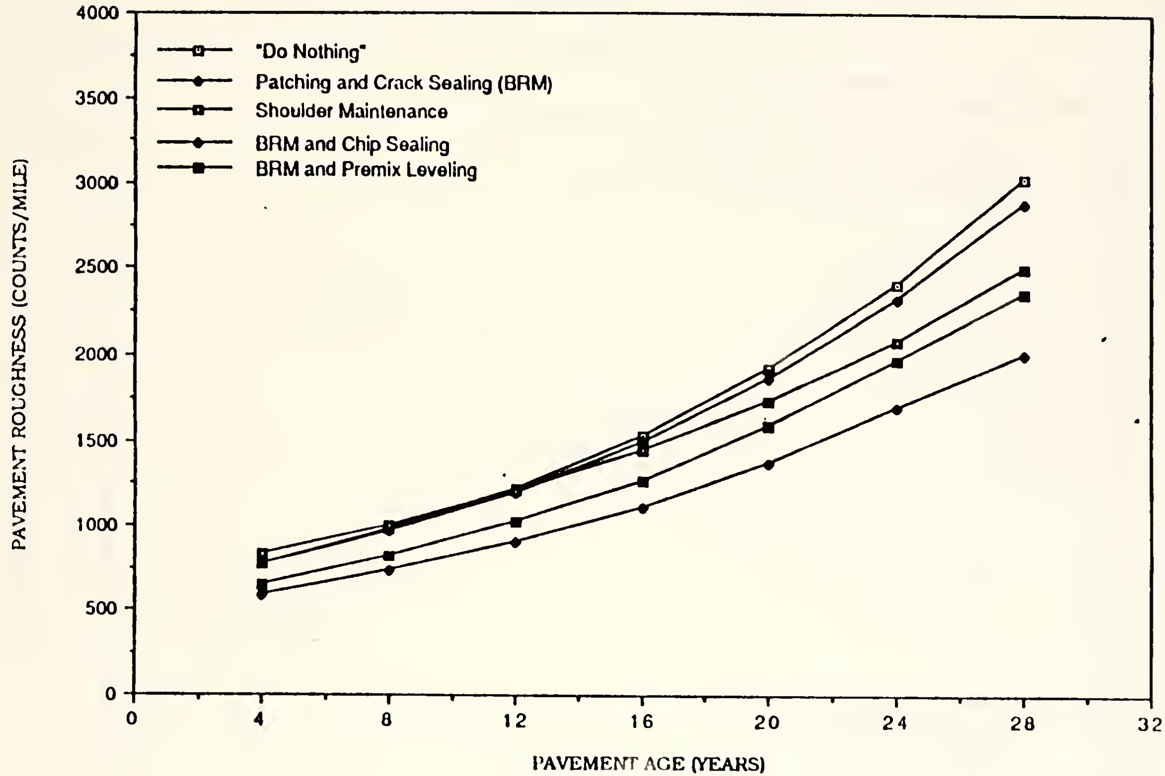


Figure 5.3

Effect of Maintenance Categories on Pavement Roughness
in the Southern Region (OSH)

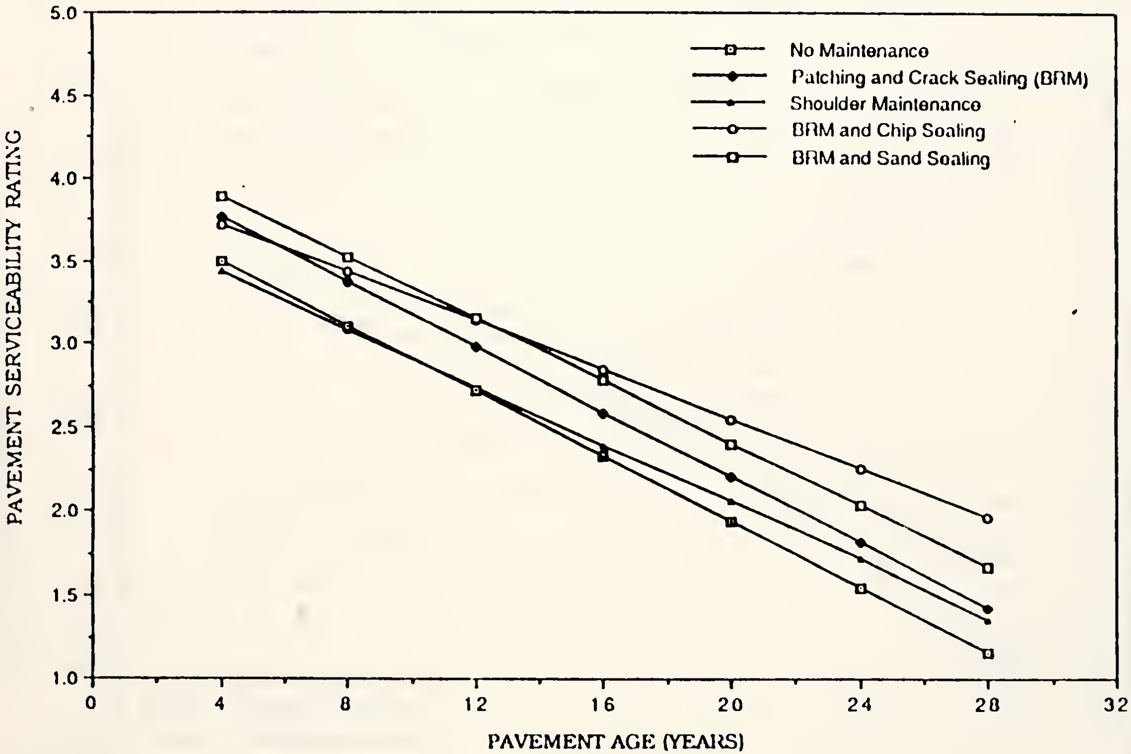


Figure 5.4

Effect of Maintenance Categories on Pavement Serviceability in the Northern Region (OSH)

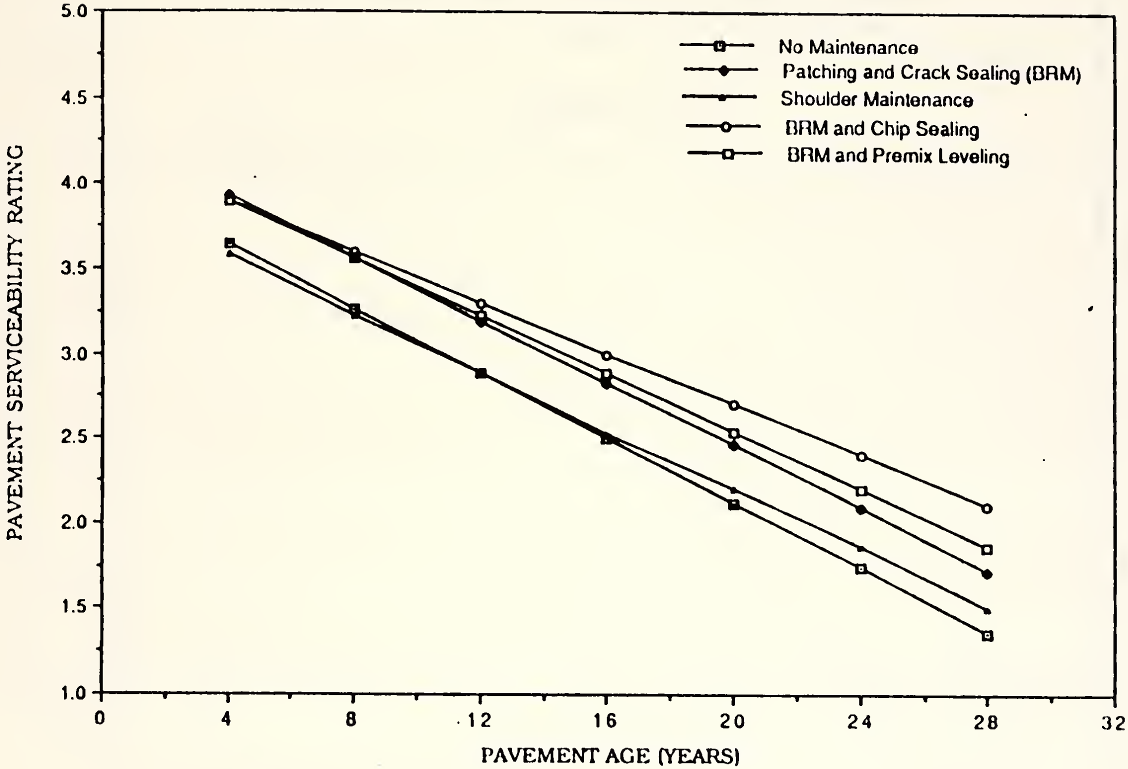


Figure 5.5

Effect of Maintenance Categories on Pavement Serviceability
in the Southern Region (OSH)

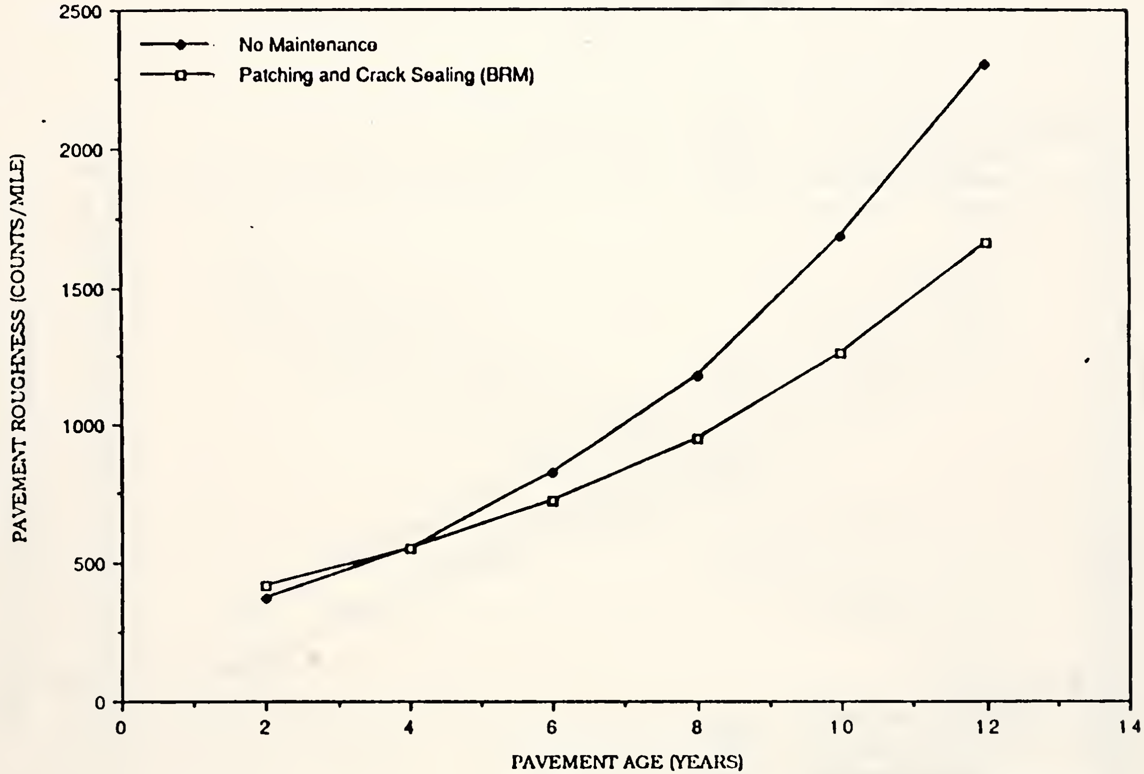


Figure 5.6

Effect of Maintenance Categories on Pavement Roughness
in the Northern Region (ISH)

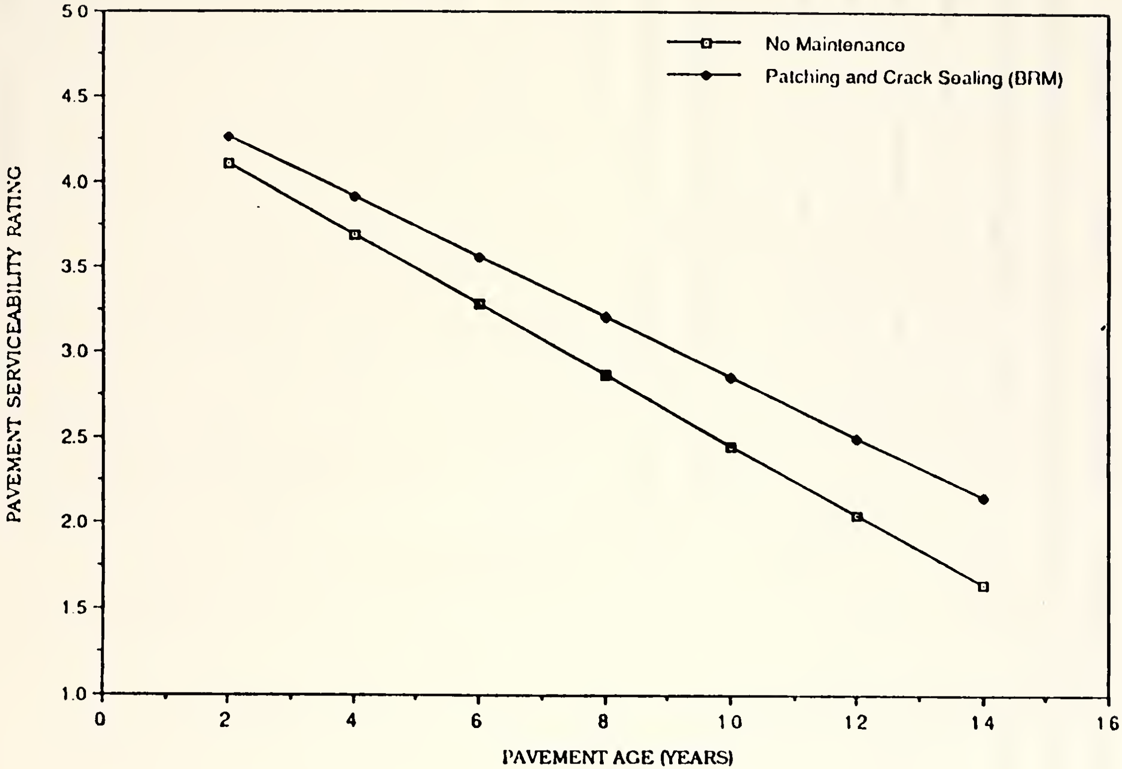


Figure 5.7

Effect of Maintenance Categories on Pavement Serviceability in the Southern Region (ISH) recorded information, such as maintenance quantities, location and type was incorrect. In addition, there were gaps in the information due to poor coordination between maintenance activities such as seal coating and data gathering activities such as skid resistance measurement.

This type of problems are to be expected in evaluations that use historical data, as opposed to experimental. From the degrees of freedom of the error terms, one can see that a large number of sections were replications; such large numbers for error degrees of freedom are not necessary for the statistical tests. Fewer sections that are properly selected, with a decent level of information accuracy and record completeness, can give much better explanation; answer more questions; and yield more reliable and stable relationships. Consequently, a long term monitoring through controlled experiments is suggested. Details of this monitoring program as well as the experimental design for such an undertaking are documented in Chapter 8.

CHAPTER 6

COST-EFFECTIVENESS EVALUATION OF CHIP AND SAND SEAL COATING

This chapter focuses on the evaluation results of the appropriate timing of seal coats. The framework and justification for the use of the least life-cycle cost (LCC) technique was presented earlier in Chapter 3. Although seal coating is used on both flexible and composite pavements, the evaluation approach is demonstrated on composite pavements. The same could be repeated on the flexible and composite pavements information obtained from the long term monitoring program proposed at the end of this report.

6.1 Mathematical Formulation of the Problem

To start with, this analysis assumes that a composite pavement section has already been overlaid and the issue is whether chip and sand seal coats are cost-effective as a maintenance strategy and, if yes, their appropriate timing. As such, the initial construction costs are considered as sunk costs. Referring to Figure 6.1, as a pavement section gets old, surface roughness increases. User cost, including vehicle operating cost, travel time cost and accident cost, as well as low order or basic routine maintenance costs, including patching, crack sealing and joint sealing, also increase. From a strict economic perspective, at the end of its life, the pavement has some salvage value, at least the value of the materials that could be recycled. However, the salvage value is small and can be included within the resurfacing cost. The accumulated total cost between the opening of the road to traffic and the time the pavement needs resurfacing would, therefore, include: the sum of the annual maintenance costs; the costs of seal coating, if undertaken, and the sum of annual user costs.

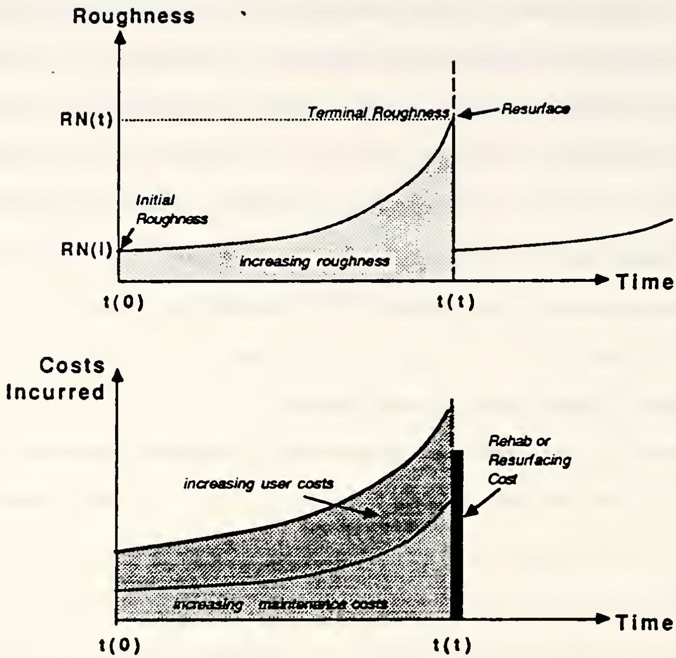


Figure 6.1

Agency and User Cost Profiles for Routine Maintenance Strategy

Refering to Figure 6.2, at a given point in time, t(s), a decision is made to seal coat the road; a certain amount of capital is then invested. Seal coating reduces the lower order routine maintenance requirements, at least for the first few years. Due to the immediate resulting improvements in roughness, user costs are expected to decline as well. In addition, the service life of the pavement is extended. The main issue here is whether the benefits accrued in terms of reduced maintenance costs, reduced user costs and opportunity costs gained due to deferment of resurfacing equate or exceed the seal coating costs.

Suppose the seal coating timing is delayed a certain period of time, say from t(s1) to t(s2), as shown in Figure 6.3. Routine maintenance to the pavement, such as more patching and crack sealing, are expected to be greater at t(s2) than at t(s1). Hence the cost for seal coating at a later date would be higher. The benefits accrued from cost reduction in user and maintenance costs could be less than the previous timing, but there are gains in the added service life. To know which strategy is better, the costs and benefits need to be discounted to a common base for comparison. A Lotus 123 spreadsheet can be programmed to carry out the economic evaluation calculations. However, a number of relationships are needed:

a. a performance function for overlaid pavements with low order or basic routine maintenance only, such as patching and crack sealing;

b. a performance function for overlaid pavements after seal coating;

c. a function relating the impact of seal coating on pavement roughness or serviceability immediately after it is applied;

d. a life expectancy relationship for seal coats as a function of the pavement condition at the time of sealing;

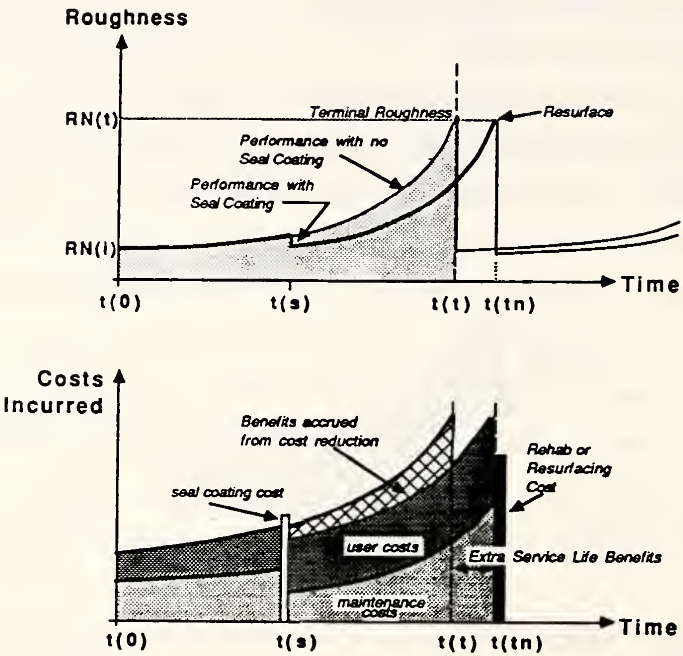


Figure 6.2

Agency and User Cost Profiles for
Seal Coating Strategy

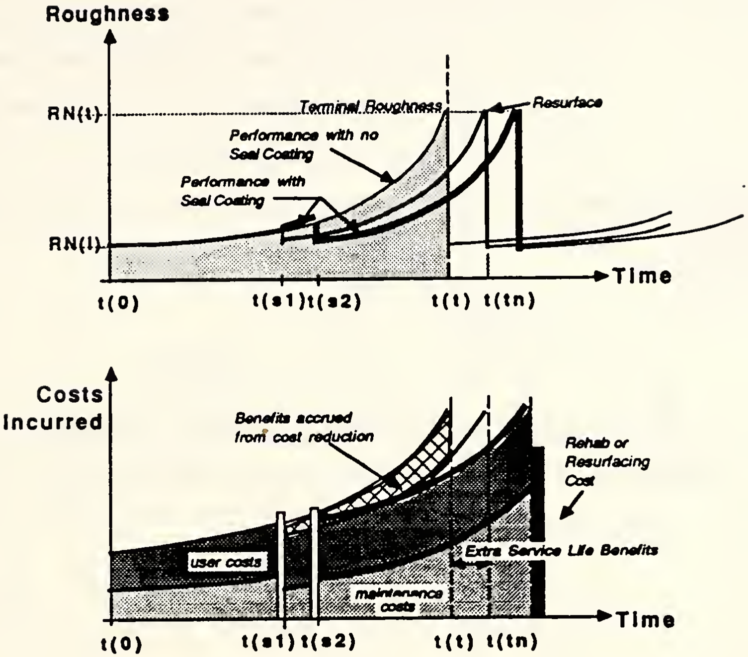


Figure 6.3

Comparison of Cost Profiles for
Two Seal Coating Strategies

e. a low order or basic routine maintenance cost function in terms of road condition; and

f. user costs as a function of road condition.

6.2 Life Cycle Costing Analysis Demonstration

This section will demonstrate the calculation mechanics of this technique. Figure 6.4 illustrates the layout of expenditures for a typical seal coating decision. Annual costs can be treated as single payments made at different time horizons, x, where x varies from 0 to n, n being the expected life of the pavement. The present worth of any annual expenditure can be calculated using the following relationship:

$$PWFE(X) = FE(x) * \{ 1 / (1+i)**x\} \qquad 6.1$$

Where PWFE(x) equals the present worth of annual expenditure in year x, and FE(x) is the annual expenditure in year x. The present worth of all annual expenditures, PWT, can be represented as follows:

$$PWT = \sum_{x=0}^{n} [FE(x) * 1/(1+i)**x] \qquad 6.2$$

If the same cycle repeats itself from year n and on, as shown in Figure 6.5, then the equivalent uniform annual cost, EUAC, calculated in perpetuity is given by the following relationship:

$$EUCA(in\ perp.) = PWT*[\{ (1+i)**n\}/\{ (1+i)**n -1\}]*i \qquad 6.3$$

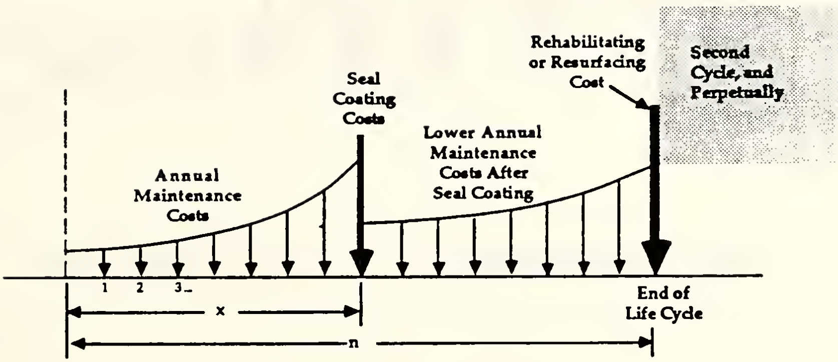
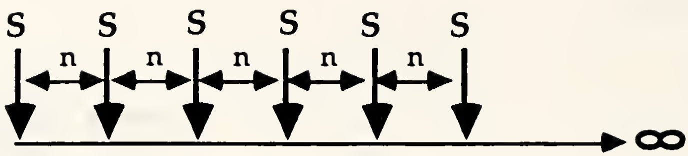


Figure 6.4

Expenditure Layout for a Typical
Seal Coating Strategy



$$\text{EUAC (in perpetuity)} = S * [(1+i)^n / (1+i)^n - 1] * i$$

Figure 6.5

Computation for EUAC (in Perpetuity)

The same relationships apply to user costs as well. Annual user costs are calculated using the following relationship:

$$UC(x) = Unit\ User\ Cost * AADT * 365 \qquad 6.4$$

where UC(x) is the user cost for year x; the unit user cost is the cost per mile for a given road roughness level; and since most state roads are two lanes, one in each direction, the reported AADT was multiplied by 0.5 to obtain the AADT per lane-mile.

6.3 Basic Relationships Used in This Study

This section will focus on the derivation of the basic functions mentioned in Section 6.1.

6.3.1 Pavement Performance With Low Order Maintenance

The curve describing pavement performance over time that was used in the evaluation is displayed in Figure 6.6. This "logistic" shape curve was derived by isolating the sections that had received only low order or basic routine maintenance and did not have volumes in excess of 3000 AADT, the range within which seal coating is normally carried out. These sections are known to receive "low order maintenance only" for 3 years in their life-time; what type of treatment they received prior to the study's 3 years is not known. In fact the scatter of points from the curve could reflect possible differences in pavement attributes or differences in levels of maintenance. However the sections were assumed to have received only routine maintenance, and the reasonableness of this assumption was confirmed when the estimated average life of the overlay from the curve (10 years at PSI = 2.2) was compared to the average

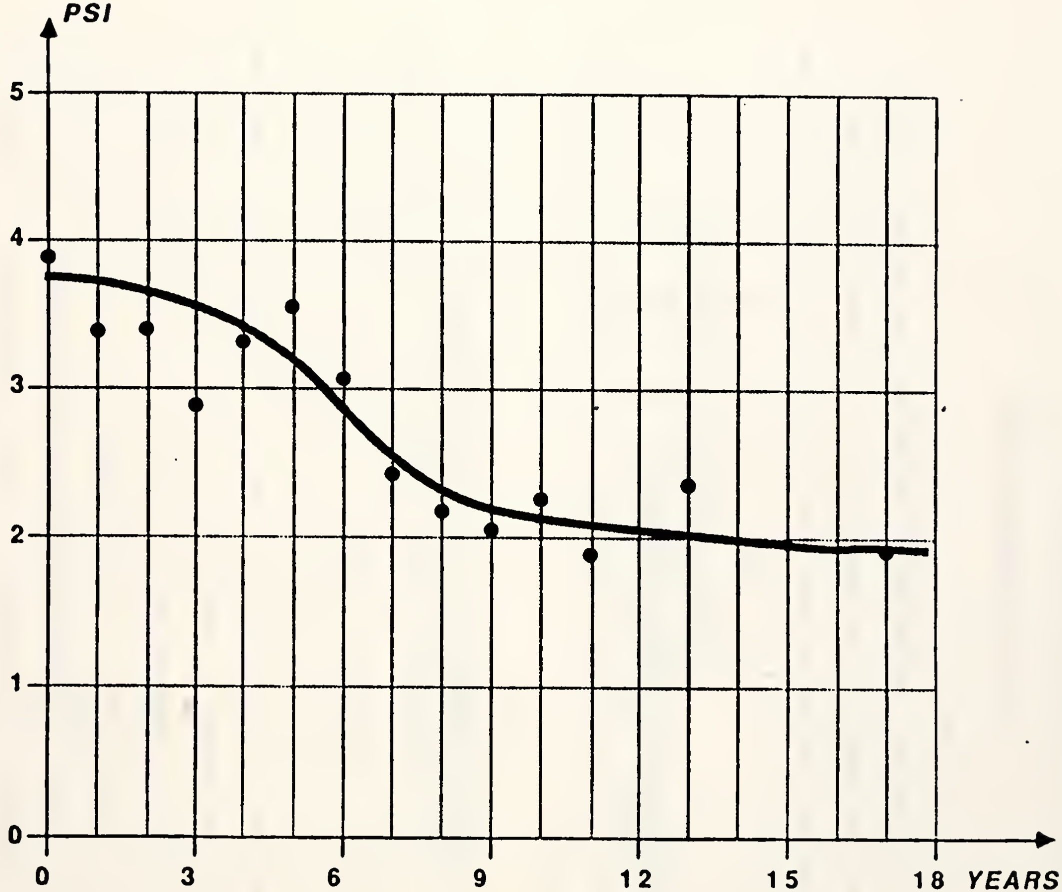


Figure 6.6

PSI as a Function of Age for Low Usage Roads (AADT < 3000) life expectancy for overlays on composite pavements as reported in the Expert Opinion Survey (9-11.8 years). The curve was estimated graphically.

6.3.2 PSI-Jump as a Function of Original PSI

Only 8 of the 22 sections receiving seal coating and included in the sample of this study carried 3000 AADT or less. The roughness data was converted to PSI using the relationship developed for Indiana [INDOT 1978]. The PSI-Jumps of those sections were calculated and plotted against their corresponding original PSI's and the resulting Figure 6.7 was obtained. Five of those 8 sections showed decline in the PSI after seal coating; the remaining three showed increases. Analysis of the sections showing decline in condition despite seal coating revealed that a possible mix of condition data with maintenance quantities could have happened. Consequently, it was decided to carry out the economic analysis of seal coating for the most optimistic scenario. Only the three sections displaying improvement in condition were used to derive the relationship, thus resulting with the following equation:

$$PSI\text{-}JUMP \begin{array}{l} = 0, \ for\ PSIoriginal <= 1.6;\ and \\ = 0.41\ (PSIorig.\ -1.6),\ for\ PSIorig. > 1.6 \end{array} \qquad 6.5$$

Since seal coating was carried out for road conditions (PSI) greater than 2.0, the latter equation was dominantly used in the analysis.

6.3.3 Pavement Performance After Seal Coating

Seal coats were reported in the Expert Opinion Survey to last on average 3.6 years. Since the analysis was carried out on annual basis, the average life expectancy of seal coats was assumed to be 4 years. Seal coating is

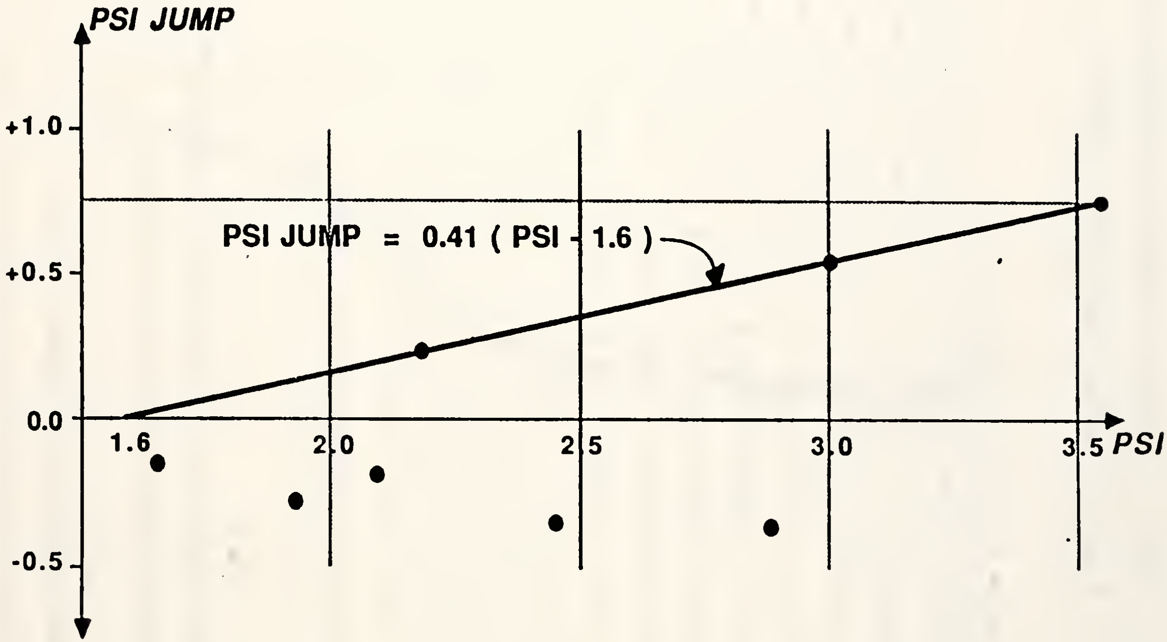


Figure 6.7

PSI Jump Due to Seal Coating as a Function of Original PSI a surface treatment; it does not add any structural strength to the pavement. It is a strategy to hold the pavement until higher order treatment becomes necessary. Therefore, it was assumed that the PSI at the end of the life cycle of the seal coat was equal to that at the beginning, that is, just before seal coating. The deterioration rate over the four years was assumed to be curvilinear and followed the normally assumed exponential form used in pavement performance. INDOT experts have pointed out that after four seal coats, pavements invariably need some form of capital work such as resurfacing or rehabilitation. In order to accommodate this phenomenon, only four seal coats were allowed as a maximum, and at the end of the last seal coat, depending on the strategy chosen, the pavement was allowed to deteriorate to PSI 2.5 where it would be resurfaced.

6.3.4 Maintenance Cost as Function of PSI

In order to obtain this relationship, the selected sections which received only low order or basic routine maintenance were isolated, and the maintenance costs were plotted against their corresponding PSI values. Figure 6.8 was thus obtained. The curve shown represents maintenance cost as required. Since after a certain threshold condition level, maintenance becomes ineffective, many agencies decide in favor of capital work.

6.3.5 User Costs as a Function of PSI

A number of studies have attempted to develop such costs. For example, in a 1975 study (OPAC), Ontario estimated user costs as a function of road roughness [RTAC 1977]. The data in this study are 15 years old and were derived for Canadian conditions (for example, more expensive fuel and parts and generally higher wages of maintenance personnel are generally experienced). Utah

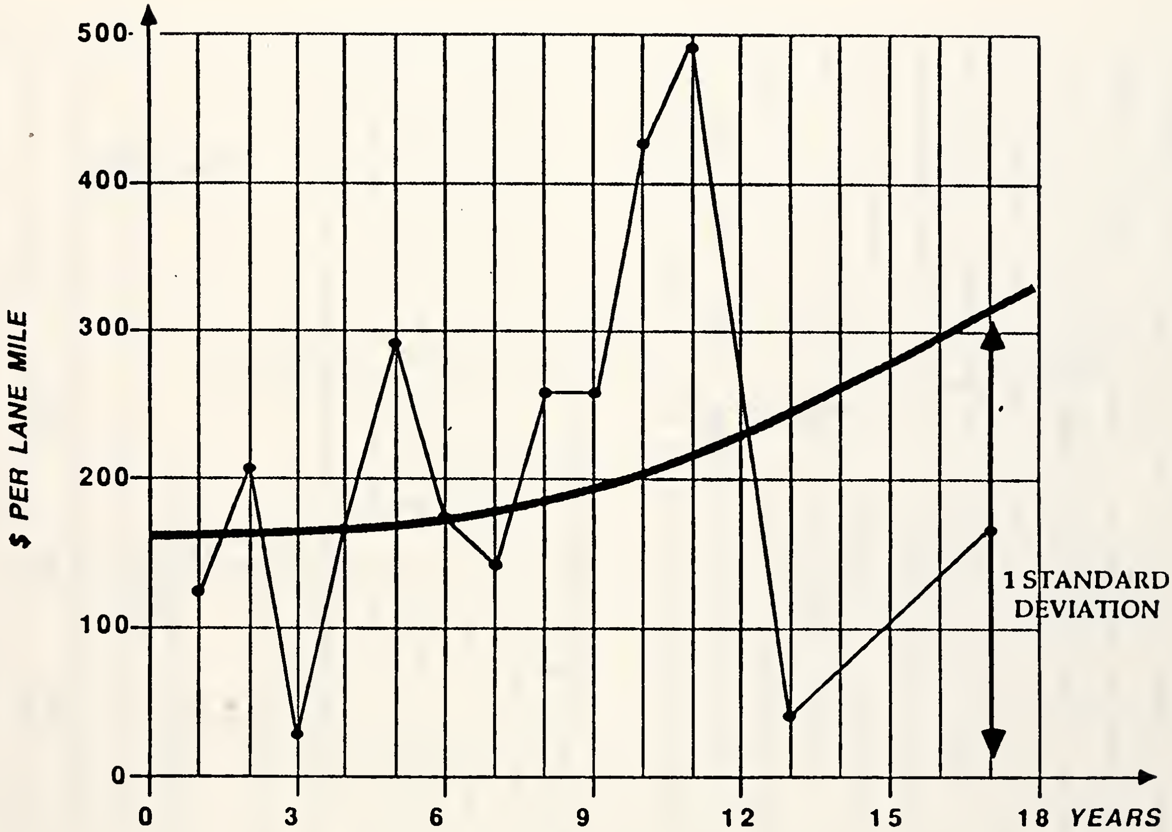


Figure 6.8

Only - Basic Routine Maintenance Cost as a Function of Age

[Peterson 1980] also attempted to develop some user costs as a function of roughness but the costs were not reliable as indicated by the study investigators. The most recent and comprehensive study on this topic was carried out by FHWA [Zaniewski 1982]. In this study, user costs were given by vehicle type and speed, pavement attributes, and roadway geometrics. The data were derived for U.S. conditions and are relatively recent. The costs recommended in the FHWA study were therefore employed in the present study. The cost figures were updated to 1987 dollars by using FHWA CPI for maintenance and operations (Equipment).

For the purpose of computation, a one-mile road section with two lanes, one in each direction was assumed. Four levels of AADT (2500, 1500, 1000, 500) with a steady speed of 50 MPH on a flat roadway were considered. The volume was assumed to comprise 12% commercial vehicles (as normally assumed for design of rural highways), with 4% being single unit trucks and 8% combination trucks. The resulting vehicle operating costs for various road roughnesses are shown in Table 6.1.

6.4 Analysis of Seal Coating Scenarios

Four different scenarios were considered: 1) no seal coating (only low order or basic routine maintenance); 2) seal coat only once in a pavement's life span; 3) consecutively seal coat twice in a pavement's life span; and 4) consecutively seal coat four times in a pavement's life span. These scenarios are shown schematically in Figure 6.9. For all these scenarios, overlays were assumed to cost \$ 50,000 per lane-mile and seal coats, \$ 2,000 per lane-mile plus the cost of the associated basic routine maintenance which varies as a function of roughness, all in 1987 dollars. The discount rate was taken as 6%. The results of each scenario test will be discussed separately below.

Table 6.1

1982 User Costs Based on FHWA Study For 0% Grade and 50 MPH, Constant Speed

	PSI					
	4.00	**3.50**	**3.35**	**3.20**	**3.00**	**2.70**
CARS (88%)						
- SMALL	103	106	107	109	111	115
- MEDIUM	122	125	126	129	131	136
- LARGE	133	138	139	142	144	150
AVERAGE	**119**	**123**	**124**	**127**	**129**	**134**
SU TRUCKS (4%)						
- PICK UP	126	130	131	134	137	143
- 2 AXLE	251	256	257	260	263	269
- 3 AXLE	371	381	384	389	394	405
AVERAGE	**249**	**256**	**257**	**261**	**265**	**272**
SEMI TRUCKS (8%)						
- 2-S2	305	315	319	323	329	341
- 3-S2	352	363	366	373	379	392
AVERAGE	**328**	**339**	**343**	**348**	**354**	**367**
OVERALL COST $/1000 MILES	**141**	**146**	**147**	**150**	**152**	**158**

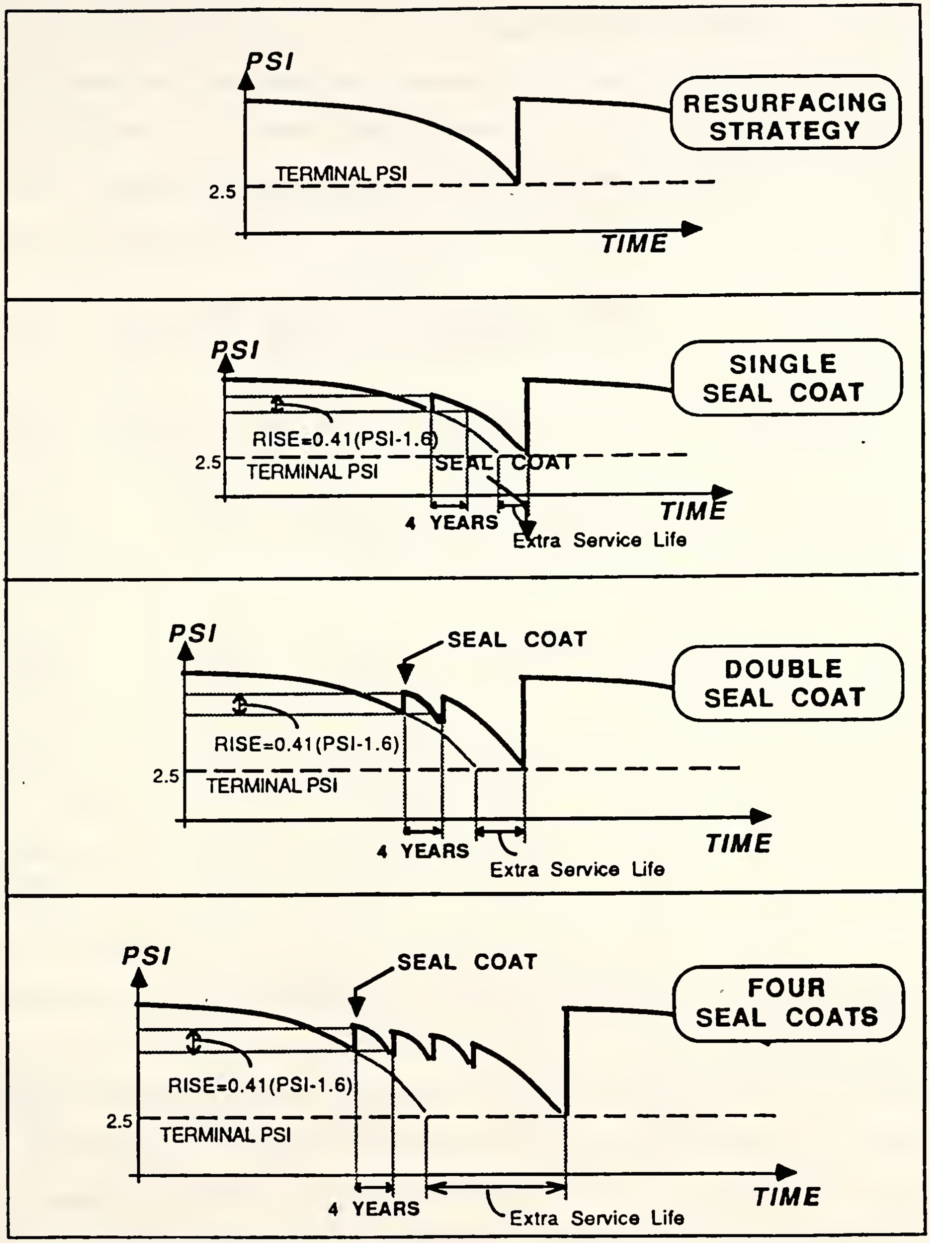


Figure 6.9

Alternative Maintenance Strategies Considered

6.4.1 No Seal Coating Scenario

In this scenario, the pavement receives only low order or basic routine maintenance until the pavement deteriorates to a threshold level (PSI=2.5), where it gets resurfaced. The threshold level of 2.5 PSI for resurfacing was used in all scenarios. The results of this analysis are as shown below:

	COST IN PERPETUITY		($/LANE MILE/YEAR)	
AADT	2500	1500	1000	500
AGENCY COST	2,607	2,607	2,607	2,607
USER COST	82,208	49,324	32,883	16,442
TOTAL COST	84,815	51,931	35,490	19,049

The agency cost in the above table does not change but the user costs naturally vary with the AADT.

6.4.2 Seal Coating "Only Once in a Lifetime" Scenario

In this scenario, the pavement was allowed to receive only one seal coat during a life cycle. The trigger point at which the seal coat to be applied, however, was varied; four PSI trigger points were tested and analyzed: 3.35, 3.20, 3.00 and 2.70. The objective of choosing these points was to study the optimal timing for seal coating.

The calculated agency and user costs are shown in Table 6.2. The table illustrates that the agency cost declines in terms of few dollars per year (in perpetuity) as the seal coat decision is postponed up to PSI of 3.0, at which time, the cost becomes fixed. On the opposite side, user costs significantly increase, in terms of hundreds of dollars per year in perpetuity. Consequently, the total cost increases in terms of hundreds of dollars and sharply increases below PSI=3.0 for all volumes of traffic. This suggests that optimal timing for seal

Table 6.2

Results of Economic Impact Evaluation of Scenario 2:
"Seal Coat Only Once in a Lifetime"

AADT:2500	COST IN PERPETUITY ($/LANE MILE/YEAR) Seal Coating Trigger PSI:			
	3.35	3.20	3.00	2.70
AGENCY COST	1,656	1,653	1,652	1,652
USER COST	79,174	79,649	80,153	80,848
TOTAL COST	80,830	81,302	81,805	82,500

AADT:1500	COST IN PERPETUITY ($/LANE MILE/YEAR) Seal Coating Trigger PSI:			
	3.35	3.20	3.00	2.70
AGENCY COST	1,656	1,653	1,652	1,652
USER COST	47,504	47,789	48,092	48,509
TOTAL COST	49,160	49,442	49,744	50,161

AADT: 1000	COST IN PERPETUITY ($/LANE MILE/YEAR) Seal Coating Trigger PSI:			
	3.35	3.20	3.00	2.70
AGENCY COST	1,656	1,653	1,652	1,652
USER COST	31,669	31,859	32,061	32,339
TOTAL COST	33,325	33,512	33,713	33,991

AADT: 500	COST IN PERPETUITY ($/LANE MILE/YEAR) Seal Coating Trigger PSI:			
	3.35	3.20	3.00	2.70
AGENCY COST	1,656	1,653	1,652	1,652
USER COST	15,835	15,929	16,031	16,170
TOTAL COST	17,491	17,582	17,683	17,822

coating is when the pavement condition reaches the PSI value of 3.0.

6.4.3 Seal Coating "Twice in a Lifetime" Scenario

In this scenario, the pavement was allowed to receive two consecutive seal coats before surfacing. The same four PSI trigger points were used for analysis in order to allow for comparison among scenarios. The results for this scenario are shown in Table 6.3. The table reflects similar trends as in the previous scenario with the optimal timing for the first seal coat being at PSI=3.0.

6.4.4 Seal Coating "Four Times in a Lifetime" Scenario

In this scenario, the pavement was allowed to receive four consecutive seal coats before resurfacing. Again the same four PSI trigger points were used. The results for this scenario are shown in Table 6.4. The same trends as in the previous scenarios were observed indicating marginal savings in agency cost and sharper increases in user costs after PSI of 3.0.

6.5 Comparisons and Conclusions

The results of alternative scenarios can be compared under a given trigger point. Considering a PSI of 3.35, the cost components for the scenarios were grouped by AADT and plotted. Figure 6.10 is a plot of the agency costs for the four scenarios. The figure illustrates a consistently declining cost function as the scenario changes from no seal coating to increasing number of seal coats during the pavement's lifetime. Figure 6.11 is the plot of user costs; the figure illustrates that sealing the pavement only once in a lifetime yields the lowest user cost for all traffic levels. Figure 6.12 is the plot of the total costs. The plot demonstrates that for AADT above 1000, the optimal strategy may be to seal

Table 6.3

Results of Economic Impact Evaluation of Scenario 3:
"Seal Coat Twice in a Lifetime"

COST IN PERPETUITY ($/LANE MILE/YEAR)

AADT:2500	Seal Coating Trigger PSI: 3.35	3.20	3.00	2.70
AGENCY COST	1,192	1,188	1,187	1,187
USER COST	80,212	80,936	81,816	82,717
TOTAL COST	81,404	82,124	83,003	83,904

COST IN PERPETUITY ($/LANE MILE/YEAR)

AADT:1500	Seal Coating Trigger PSI: 3.35	3.20	3.00	2.70
AGENCY COST	1,192	1,188	1,187	1,187
USER COST	48,127	48,562	49,089	49,630
TOTAL COST	49,319	49,750	50,276	50,817

COST IN PERPETUITY ($/LANE MILE/YEAR)

AADT: 1000	Seal Coating Trigger PSI: 3.35	3.20	3.00	2.70
AGENCY COST	1,192	1,188	1,187	1,187
USER COST	32,085	32,375	32,726	33,087
TOTAL COST	33,277	33,563	33,913	34,274

COST IN PERPETUITY ($/LANE MILE/YEAR)

AADT: 500	Seal Coating Trigger PSI: 3.35	3.20	3.00	2.70
AGENCY COST	1,192	1,188	1,187	1,187
USER COST	16,043	16,187	16,363	16,543
TOTAL COST	17,235	17,375	17,550	17,730

Table 6.4

Results of Economic Impact Evaluation of Scenario 4:
"Seal Coat Four Times in a Lifetime"

AADT:2500	COST IN PERPETUITY ($/LANE MILE/YEAR) Seal Coating Trigger PSI:			
	3.35	3.20	3.00	2.70
AGENCY COST	754	748	744	742
USER COST	81,211	82,154	83,134	84,490
TOTAL COST	81,965	82,902	83,878	85,232

AADT:1500	COST IN PERPETUITY ($/LANE MILE/YEAR) Seal Coating Trigger PSI:			
	3.35	3.20	3.00	2.70
AGENCY COST	754	748	744	742
USER COST	48,727	49,293	49,880	50,694
TOTAL COST	49,481	50,041	50,624	51,436

AADT: 1000	COST IN PERPETUITY ($/LANE MILE/YEAR) Seal Coating Trigger PSI:			
	3.35	3.20	3.00	2.70
AGENCY COST	754	748	744	742
USER COST	32,485	32,862	33,253	33,796
TOTAL COST	33,239	33,606	33,997	34,538

AADT: 500	COST IN PERPETUITY ($/LANE MILE/YEAR) Seal Coating Trigger PSI:			
	3.35	3.20	3.00	2.70
AGENCY COST	754	748	744	742
USER COSTS	16,243	16,431	16,627	16,898
TOTAL COST	16,997	17,179	17,371	17,640

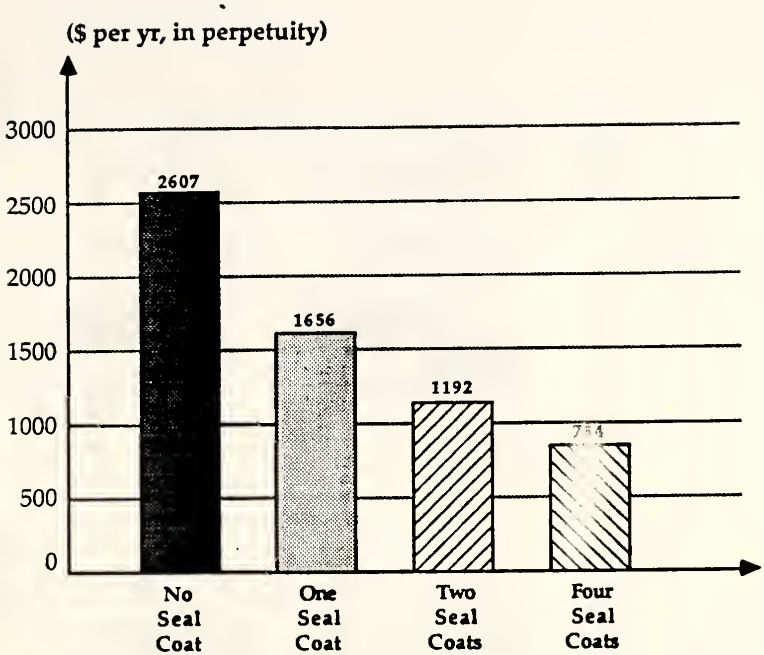


Figure 6.10

Comparative Evaluation of Agency Costs for the Four Seal Coating Scenarios at PSI = 3.35

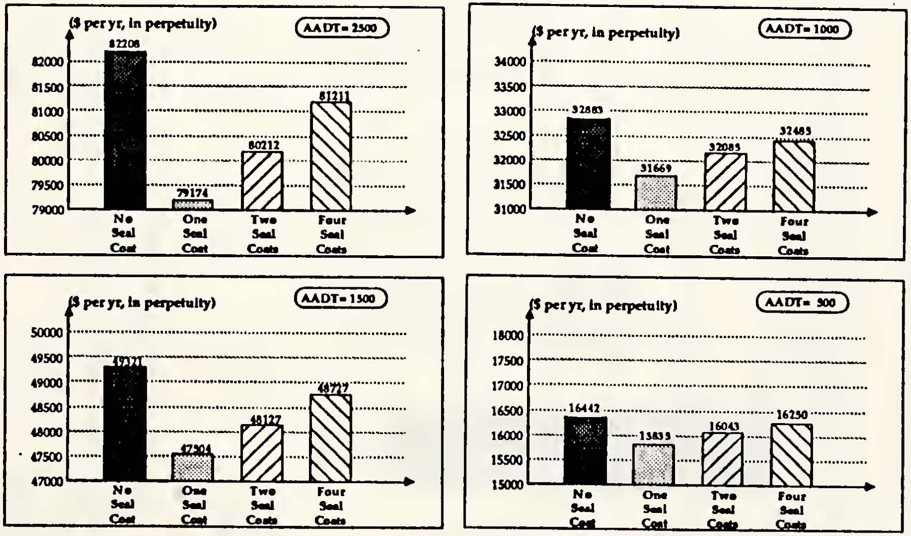


Figure 6.11

Comparative Evaluation for User Costs for the
Four Seal Coating Scenarios at PSI = 3.35

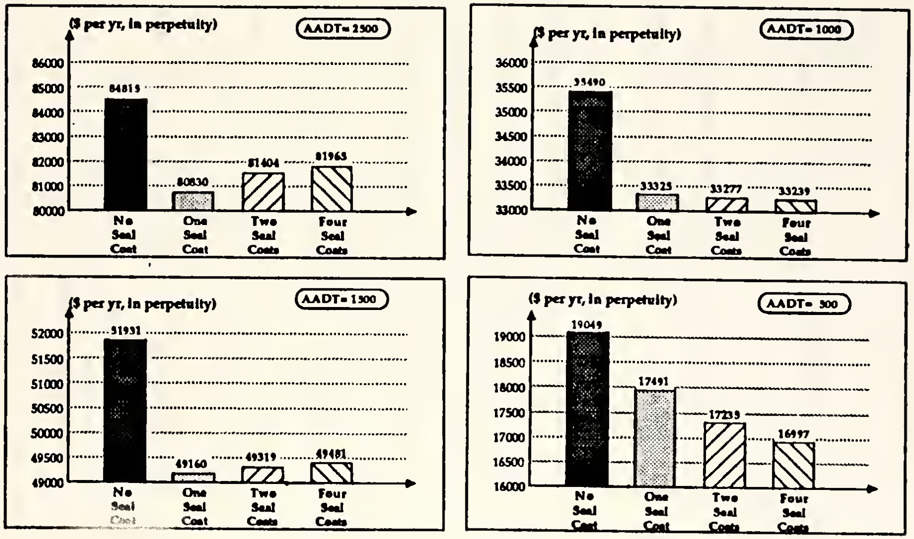


Figure 6.12

Comparative Evaluation of Total Costs for the
Four Seal Coating Scenarios at PSI = 3.35

coat only once; however, as the traffic volume decreases, two to four seal coats before resurfacing can be justifiable. The drops in total costs are illustrated in Figure 6.13, using vectors, with the one seal coat scenario being the reference point. It can be shown that for AADT less than 1000, the vectors are always negative.

The above analysis suggests a number of important conclusions and directions, including the following:

1. From the agency viewpoint, seal coating offers two advantages: increased flexibility in programming capital works and some dollar savings in the long run.
2. Since the use of one, two, three or four seal coats determines how long the expensive resurfacing is delayed, and since each seal coating can buy an extra four years of service life, the agency can perpetually save up to 70% of its overall annual maintenance costs (from $ 2607 per year for no seal coat to $ 754 per year for four seal coats).
3. Past the 3.00 PSI level, the agency savings almost disappear and the user cost rises sharply. This would suggests that seal coating should be considered when the pavement is in generally fair condition (around PSI of 3.0). Using the performance curve that was developed in this study, this condition would normally occur when the pavement is roughly 5 years old.
4. Seal coating is more of a stop-gap measure to avoid otherwise excessively deteriorated conditions due to shortage of funds required to do the required treatment; In this sense, it is a cost-effective solution to problems.

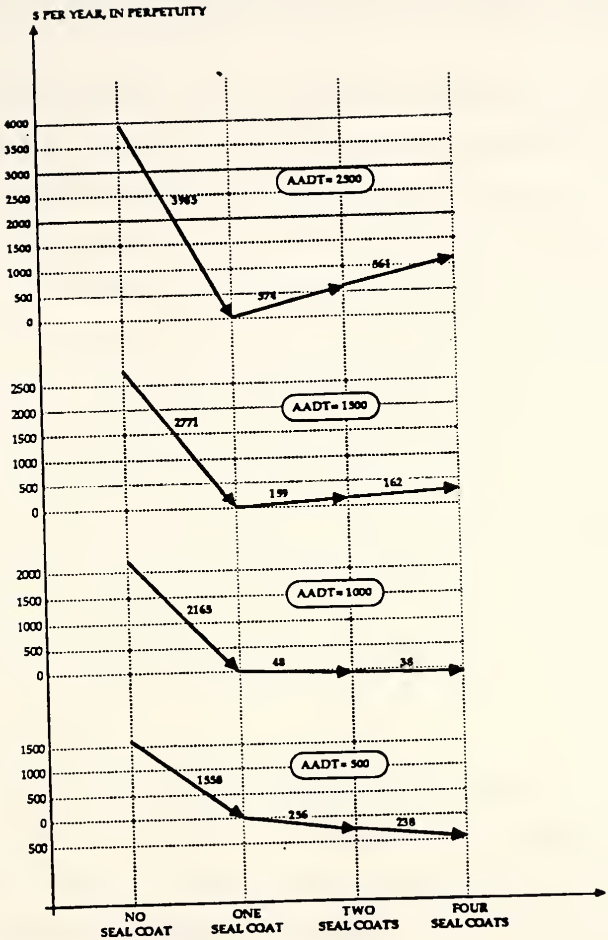


Figure 6.13

A Demonstration of the Drop in Total Costs for the Four Seal Coating Scenarios Using Vectors

CHAPTER 7

CHIP AND SAND SEAL COATING ACTIVITY MANAGEMENT GUIDELINES

As discussed earlier, chip and sand seal coating are the most expensive routine maintenance activities; both are generally associated with a high impact on pavement performance such as skid resistance and pavement serviceability rating. However, the missing link in Indiana, as discussed in Section 3.3.3, is that no formal guidelines exist for the management of the chip and sand seal coating activities at the project level; what is needed is a set of criteria for guiding decisions on specific roadway sections (whether to seal coat and when). Such decisions are currently left to the personal judgement of district maintenance engineers. As a result of this practice, a significant variance in the utilization and application of these two seal coats among the six districts exists. It is desired to develop management guidelines for bringing consistency in the management of this activity across the State. The current chapter deals with this specific desire and proposes a set of guidelines (in the form of a decision tree) for that purpose.

A number of sources were consulted in the development of the proposed guidelines. 1) Phone interviews with a number of highway department officials in select states in the U.S. (Texas, Utah, Colorado) were carried out. 2) Phone interviews with select research institutions such as Texas Transportation Institute, the Asphalt Institute, and ERES Consultants, Inc., were also carried out. 3) An opinion survey of a dozen experts in INDOT (from Central and District Offices) was conducted. 4) Documents supplied by the Federal Highway Administration [U.S.Government 1989, Papet 1989] were reviewed. 5) A literature search of published experiences and guidelines from other jurisdictions in U.S. and

Canada (Maine, Pennsylvania, Florida, Utah, Colorado, South Carolina, Connecticut, California, Nova Scotia, Saskatchewan, New Brunswick) was carried out; and 6) findings from this study were also utilized.

A digest of other jurisdictions' experiences with chip and sand seal coating is first presented; then, the current practice in Indiana is summarized; and lastly, the recommended policy guidelines are presented and discussed.

7.1 Digest of Other Jurisdictions' Experiences

Chip and sand seal coating involve the application of one or more layers of asphalt-based bituminous materials, each followed by the application of cover aggregates (in varying thicknesses) to pavements with asphaltic surfaces (flexible or composite), but not rigid. In the case of chip seals large aggregates (gravel, rock screenings or slag) are used; in sand seals, sand (natural or rock screening) is used.

7.1.1 Purpose

Sand seals are used to restore a dry, weathered or oxidized surface; the seal coat layer helps prevent the loss of material due to traffic wear. It prevents the intrusion of moisture and air, when the existing pavement surface begins to crack, to the underlying pavement structure. If allowed to penetrate, the air accelerates oxidization and the water weakens the bond between the asphalt overlay and the underlying concrete slab or base. Sand seals are also used on pavements that have lost some of its matrix (the fine aggregates surrounding the larger rocks in the asphalt mix) and where tightening the pavement texture and reducing raveling are desired. If the selected sand is clean, sharp and angular, significant improvements to surface texture and hence skid resistance, can be obtained. Clean pavement surface, controlled temperature (124-185 deg.F) of the asphalt cement, and good sand cover at the time of treatment are essential for successful application.

Chip seals are usually built as a blanket cover on pavements suffering from loss of skid resistance, oxidization, raveling, spalling, erosion, permeable surface or developing signs of aging and distress as manifested in the form of light alligator cracking. Because of the larger thickness of chip seals, they are considered by many as superior to sand seals, but they are more expensive as well (in Indiana, costing almost twice as much). In certain jurisdictions, sand sealing is used as a first crack filling layer, followed by the more durable chip seal. The effectiveness of chip seals is, in turn, influenced by a number of factors relating to the condition of the surface to be sealed; the materials used in the mix; the construction technique; the weather; and traffic control during and after seal coating.

7.1.2 Overall Usage

Some agencies such as the California Department of Transportation [CalTrans 1983] treat seal coating as one of the solutions in their list of maintenance strategies dealing with distressed pavements; when certain road conditions develop, seal coating is considered as a solution. Others use it only as a stop-gap measure to defer capital spending. For example, Saskatchewan [Scott 1986] uses seal coating only towards the end of life of pavements in order to buy some time before they rehabilitate the road. It is sometimes used on older pavements only in response to certain distress conditions and, at other times, on middle aged pavements as a preventive strategy to keep it rejuvenated, thus reducing overall maintenance costs.

7.1.3 Management Criteria

Although the literature is rich with information on chip and sand sealing experiences, most of the information deals with experimentations with different materials, conditions and or application rates. None of the contacted jurisdictions had documented formal management guidelines that they could share with this study. Similar to Indiana, most of the interviewed states tended to leave the management criteria development and application to their field enginee-rs although many reported that criteria for their jurisdiction were under development. Field engineers, it was reported, made judgements whether to seal coat or not based on visual inspections of the road section's condition (slip-periness, raveling, and so on). Although field engineers decide whether the sections require seal coating or not, some states (Texas, for example) have enticed their field engineers to use seal coating by dedicating a special fund for the activity valued at 145 million dollars in 1987. The Preventive Maintenance Program, as it is called, does not require project approval for seal coating. This triggered the interest of their maintenance staff in seal coating as a strategy for road treatment and, consequently, their seal coating program expenditure grew very fast in the last few years. As a result of a survey of state departments of transportation, fourteen states were also reported to use plans of seal coating every X number of years, where X varied from state to state [Skok 1980].

Some criteria proposals were found for the Minnesota Local Road Research Board [Skok 1973], parts of which were subsequently adopted by the Utah Department of Highways, particularily in the area of priority setting [Peterson 1974]. The proposed criteria were based on a special rating scheme (0-5) on each of the surface distresses used in the criteria (shown on Figure 7.1); these pub

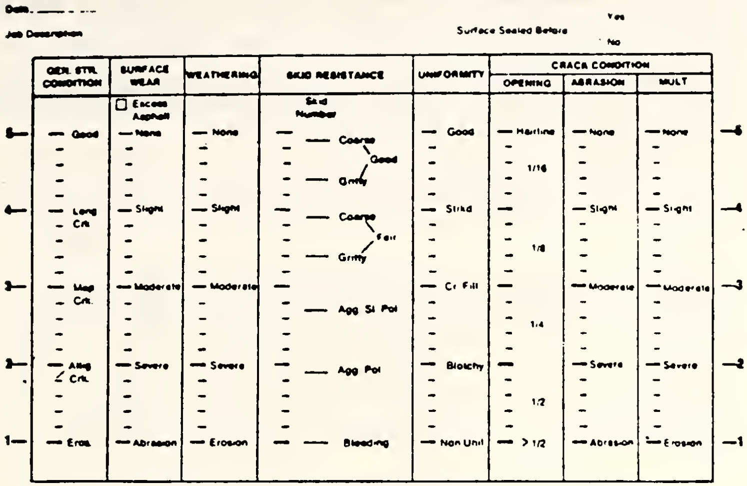


Table 1 Rating for degrees of pavement surface wear (no seal coat).

Rating	Degree	Description
5	None	Mat uniform, and original color across surface
4	Slight	Coarse aggregate shows in wheel path but not protruding
3	Moderate	Coarse aggregate shows in wheel path and protrudes up to 1/16 in. (2 mm), or wheel path is worn down to 1/16 in.
2	Severe	Coarse aggregate protrudes in wheel path more than 1/16 in. (2 mm), or mat is worn down more than 1/16 in.
1	Abrasion	More than 20 percent of coarse aggregate is kicked out in the wheel path

Figure 7.1

Surface Condition Survey Form Recommended to Minnesota Department of Highways

[Source: Skok 1973]

lished criteria included:

1. If the original surface is a plant-mixed, machine laid surface and the rating for the wear, weathering or skid resistance is 3.0 or lower, the pavement should be considered for a seal coat. If the rating of any of these is 2.0 or lower, the pavement should definitely be seal coated or resurfaced in some manner, especially if the ADT is greater than 1000.

2. If the original surface is a surface treatment or road mix, the same criteria should apply, except that the pavement definitely should be resurfaced if the ADT is 500 or greater.

3. If the surface rating for uniformity is 2 or less for any type of surface, the pavement should be considered for seal coating. If the rating is 1, the pavement definitely should be seal coated.

4. For setting up a seal coat program within a given agency, the pavements exhibiting low ratings relative to skid resistance, surface wear and weathering should be given priority in that order. However, any pavement that has a rating of 2.0 in any of the categories should be given priority over one that has a rating higher than 2.0. Also those pavements with a rating of 3.0 or less in surface wear, weathering or skid resistance should be given priority over those considered because of uniformity.

7.1.4 Traffic

Seal Coating is generally used on "low" volume roads because the seal coat is not strong enough to stand the wear and erosion caused by heavy loads or traffic. The abrasive action of traffic causes the fine matrix to wear, leaving behind coarse aggregates protruding, which in turn get kicked out of place. This phenomenon is sometimes called "dusting", and in fact could be used as a measure for determining the timing for seal coats. "Erosion" usually occurs in the wheel paths, by forming channels similar to those caused by rutting. The word "low" has variable definition. Some use it to imply a maximum traffic level of 1500 AADT; others, 2000; and some others 2500. One practice, though, seems definite: this type of treatment is not applied on heavily used highway sections in or near urbanized areas. Traffic, therefore, would be an influential factor in determining at what pavement rating level seal coating would be appropriate.

Because high volumes of traffic can cause flying stone problems, smaller maximum size aggregates and plant-mixed seals or precoated chips need to be used. Hence traffic would also influence the material specifications for seal coats and the traffic control requirements during construction. Most jurisdictions reporting on the use of chip and sand seals indicated the use of sand seals with slightly lower traffic volumes than for chip seals.

7.1.5 Climate

The effect of climate is evident in three different situations: firstly, in a relatively warm but moist climate, it may be more appropriate to use a thin overlay than chip and sand seals because of the aggregate retention problems created by the slow curing of the seal coats; secondly, if the climate is humid and cool, constructing good sand and chip seal coats, or a thin overlay, would be very difficult (aggregate retention problems in the case of the two seal coats, and compaction problems with the case of the thin overlay); thirdly, Colorado reported some bad experience with crumb rubber chip seal coating in experiments performed at locations that are subjected to high precipitation (average annual 12.2 inches), and high seasonal temperature fluctuations (in the order of 115 to 125 deg.F in one summer), where traffic was about 2000 AADT (with 14% heavy trucks) [Laforce 1983]. Experiments subjected to heavy snow plow blade action, where packed snow was frequent and thick, also resulted in the seal coats being badly damaged after one season [Laforce 1983]. In general, weather conditions do influence the timing of seal coats.

7.1.6 Structural Condition

It is fully agreed among all that seal coats do not add any appreciable strength to the pavement layer. They are surface dressing aimed at restoring surface properties only. Moreover, even the surface properties are restored, the aging process of the pavement structure continues. Hence, seal coats are not expected to arrest a condition of extreme alligator cracking or other fatigue distresses like transverse and longitudinal cracks. In such cases, the seal coat may last for one season only, where the cracks would reflect onto the new surface.

In brief, if structural problems like fatigue cracking, rutting, or heave exist, the seal coat will not be effective in restoring rideability or stopping the deterioration. Other major work like drainage improvements to the subbase or subgrade or strengthening of pavement structure would be required. Hence, seal coating in this case is a waste of time and money.

The Utah DOH uses the structural strength of the road measured by a dynaflect device, along with other road condition related factors (skid resistance measurements and sufficiency ratings) in the setting of their seal coating priorities via a computer program [Shephard et al. 1980].

7.1.7 Pavement Surface Condition

The condition of the surface seems to have an impact on the effectiveness of seal coats . A study for the Illinois DOT demonstrated clearly that the effect of seal coating on pavement condition index or roughness is dependent on the condition of the pavement when the seal coat was applied [Smith 1987]. The life expectancy of the seal coat is also dependent on the pavement condition at the time of application.

7.1.8 Material Used

Different materials have been tested for improving seal coats. Examples include the use of rubber modified asphalts (asphalts with ground reclaimed tire rubber); high float emulsion asphalts; rapid setting (cationic) asphalts; open-graded, plant-mixed seal coats; and epoxy chip seals. These experiments were carried out in an attempt to improve the effectiveness of seal coats in terms of skid resistance restoration; reduce the frequency or speed of reflective cracking development; or cut down the costs of seal coats [Oliver 1981, Huff and Vallerga 1981, Page 1977, Laforce 1986]. In some of these materials (e.g., use of rubber modified asphalts), conflicting experiences were reported [Laforce 1983, Scott 1986, Huff and Valerga 1981, Stephens 1989, Decker et al. 1979, Brownie 1976]. It is important, therefore, to be familiar with the specifics of any of these experiments before utilizing the experiment's conclusions.

7.1.9 FHWA Policy

At the federal level, the FHWA's pavement policy is aimed at providing serviceable pavements in a cost effective manner [FHWA 1989]. It attempts to do so by establishing definitions, policy statements and requirements for eligibility of funding. The policy has many components some of which affect maintenance including seal coating. The components that affect maintenace include the following points [Papet 1989]:

a. The FHWA pavement policy mandates that each state must have a Pavement Management System (PMS) that provides the decision makers with a set of tools or methods to find cost effective strategies for providing, evaluating, and maintaining pavements in a serviceable condition. Such systems should be capable of providing information (data, analysis capability, and outputs) for the effective and efficient management of their highway pavements (including design, rehabilitation and maintenance levels).

b. The requirement of a minimum pavement performance period (minimum of 8 years, with exceptions to as low as 5 years upon FHWA approval) from newly constructed, rehabilitated or reconstructed pavements implies that maintenance strategies like seal coating should be considered as a stop-gap measure in achieving these minimum levels of performance. It is expected that each state will perform adequate and timely maintenance of the pavement and shoulder with state funds.

c. The requirement that every pavement project, whether construction or rehabilitation, must have a skid resistant surface implies that seal coating could be a corrective strategy if adequate skid resistance is not achieved during construction.

d. The eligibility for Federal-aid funding to be based on an economic analysis requires the development of tools such as life cycle costing. It is inappropriate for the state to let maintenance of any item lapse in order to obtain Federal-aid funds.

The gist of the FHWA pavement policy framework, therefore, is effective investments, where seal coating should be applied, if so required, as a means for achieving that effectiveness.

7.2 Indiana's Practice

In Indiana, both chip and sand seal coats are used. INDOT is in charge of some 11,285 miles of highways and state roads adding up to 28,203 lane miles

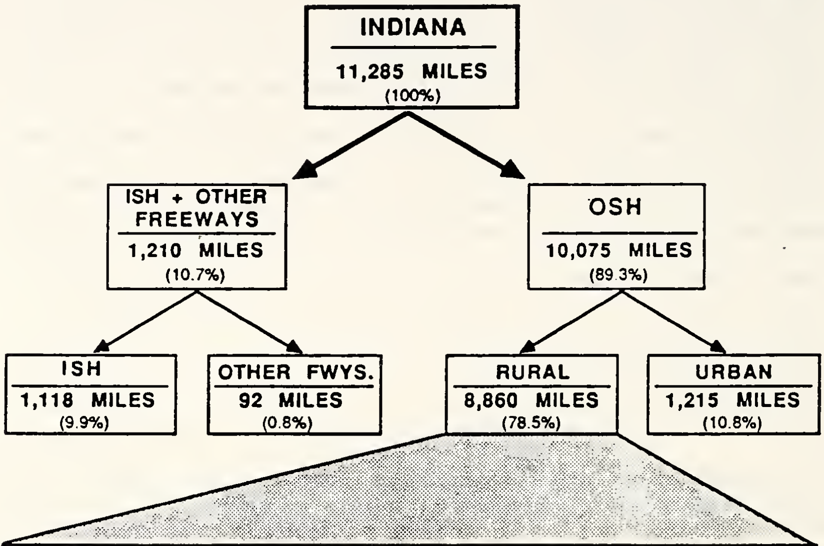
[INDOT 1988]. The majority of this mileage is in the non-interstate category (about 10,075 miles). Of these 10,075 miles, 8860 miles (about 88%) are rural and 1215 miles (about 12%) are urban. Since urban highways tend to carry heavy loads, and since seal coating is normally applied on non-curbed, low volume roads with flexible or composite pavements, it is the rural part that is of interest to this study. Of the rural roads, 787 miles are made of portland cement concrete (about 8.9%) and those roads are not considered at all for this activity. The actual mileage of 8073 miles of flexible and composite pavements is thus a possible candidate for seal coats. In reality, only roads carrying low volumes (less than or equal to 3000 AADT) would normally be candidates for seal coating. Table 7.1 summarizes the above described breakdown and provides a distribution of the potential roads for seal coating on a maintenance district basis.

7.2.1 Seal Coating Activity

INDOT keeps a series of annual Surface Change Reports that include most resurfacing and seal coating undertakings in every district during a given year. These reports are the outcome of optional reporting practice by the districts; consequently, they do not necessarily include all of the undertakings. Hence, the information derived from these reports represent the minimum level of seal coating activities in a given year. The reports for the years of the study period, 1984-1986, were summarized. The summary indicated that during the period of three years, at least 2934 miles of roadway were seal coated. Most of the seal coats were chip seals (about 90%). The extent of seal coats in seven districts during 1984-86 was as follows: Laporte - 792.6 miles; Crawfordsville - 718.4 miles; Vincennes - 510.9 miles; Fort Wayne - 499.6 miles; Greenfield - 223.3 miles; and Seymour - 193.4 miles. Several observations can be made from

Table 7.1

Classification of Roads in Indiana Under State Jurisdiction



DESCRIP. \ DISTR.		CRAWFORDSVILLE	FORT WAYNE	GREENFIELD	LAPORTE	SEYMOUR	VINCENNES
TOTAL MILEAGE		1506	1617	1097	1401	1617	1622
CONCRETE	% OF TOTAL	9	6	14	10	9	7
CONCRETE	MILES	136	97	154	140	146	114
BITUMINOUS SURFACE FLEXIBLE & COMPOSITE (MILES)		1355	1520	943	1261	1471	1508

a. Different districts have different levels of use of seal coating in maintenance. For example, during 1984-86, Laporte and Crawfordsville applied seal coating in the range of 240-265 miles per year; Fort Wayne and Vincennes, 165-170 miles per year; Greenfield and Seymour, 65-75 miles per year;

b. Different districts have different inclinations towards either type of seal coat. For example, Laporte, Greenfield and Seymour were almost exclusively in favor of chip seals, whereas Crawfordsville, Vincennes and Fort Wayne made some use of sand seals.

c. Even if two districts favored a given seal coating type (i.e., chip or sand), they did not necessarily favor the same type of seal coating practice.

Table 7.2 presents the relative scale of seal coating activity in Indiana during 1984-86. At the state level, 12.2% of the roads were seal coated annually, with average annual seal coating activity variation within the districts from a low of 4.4% to a maximum of 20.9%.

7.2.2 INDOT Expert Opinion on Seal Coating

In order to obtain better understanding of the decision making environment in Indiana with regards to seal coating, an "Expert Opinion Survey" was mailed to 16 experts within INDOT. Ten responses (5 from the districts and 5 from central office) were received and analysed. A number of observations related to the range of means of the responses and conclusions relating to the practice of seal coating can be stated:

Table 7. 2

Relative Scale of Seal Coating Activity in Indiana 1984-86

DESCRIP. \ DISTR.		CRAWFORDSVILLE	FORT WAYNE	GREENFIELD	LAPORTE	SEYMOUR	VINCENNES
BITUMINOUS SURFACE FLEXIBLE & COMPOSITE (MILES)		1355	1520	943	1261	1471	1508
AVERAGE ANNUAL Seal Coat MILEAGE		240	166	74	264	64	171
AVERAGE ANNUAL SEAL	TOTAL MILES	240	166	74	264	64	171
	% OF BITUM.	17.7	10.9	7.8	20.9	4.4	11.3

a. For chip seals, the two primary factors considered were pavement condition and traffic; two secondary factors were roughness and age. For sand sealing, pavement condition and age were primary factors, and only roughness was a secondary factor.

b. Chip seals are generally considered when the overlay in composite pavements is about 7 to 8 years old (7.6 years on average), and when the flexible pavement is 7 to 9 years of age (8.1 years on average). For flexible pavements, other factors considered in deciding chip sealing include: roughness in the order of 1150 and traffic being below 2250 AADT, on average.

c. Sand seals are generally considered when the overlay in composite pavements is about 5.5 to 6 years old (5.8 years on average), when roughness is in the vicinity of 1400. For flexible, it is considered when the age is about 6.0 years, roughness less than 1200, and traffic is below 2200 AADT.

d. Overlays last on flexible pavements in the order of 13 years whereas on composite, only 10 years.

e. 90% of the respondents are of the opinion that chip seals are effective and should be continued in use, whereas only 64% of the respondents shared the same position for sand seals. In addition, chip seals were ranked equal to sand seals when applied on pavements with good condition, but superior when applied on pavements of fair or poor condition.

f. Generally, common objectives for maintenance, including seal coating activity, were not shared by all of the respondents; in fact, the term "objective" meant differently to different participants.

Consequently, no single objective stood out as a main one.

g. The average life expectancy of chip seals on both flexible and composite pavements followed a similar trend, and varied by pavement condition: when applied on poor pavements, they last from 1.4 to 2.7 years; on fair pavements, from 2.3 to 3.8 years; and on good pavements, from 3.5 to 5.4 years.

h. The average life expectancy for sand seals was generally lower than that of chip seals and varied in trend between flexible and composite. When applied to flexible pavements of poor condition, sand seals tend to last from 0.5 to 1.5 years; on fair pavements, from 1.3 to 2.3 years; and on good pavements, from 2.4 to 3.75 years. On composite pavements, however, sand seal coats tended to last a bit longer: 1.4 to 2.4 years when applied on poor pavement condition; 1.9 to 3 years when applied on fair conditions; and 2.6 to 4 years when applied to good conditions.

The responses indicated variation among the districts, within central office and between central office and districts with respect to the treatment life expectancies as well as to the desirability of seal coats.

7.3 Policy Guidelines

Seal coating activities are better anchored to specific surface deficiencies like raveling, weathering, oxidization, skid resistance, and so on, than to generalized indicators such as RN and PSR. Specific surface distress information is not currently available within INDOT. Hence, the developed policy guidelines were geared towards currently gathered information; future guidelines may be redesigned to include the more meaningful and then procurable surface condition indicators. This will be dealt with in Chapter 8, under Long Term Monitoring. The developed guidelines were reviewed by INDOT District Maintenance representatives in a special meeting that took place on Friday, July 20, 1990. Useful dialogue took place at the meeting and the guidelines were revised accordingly. Following is a review of the logic underlying the developed policy guidelines; a list of the developed guidelines themselves, and a proposed procedure for the use of the guidelines.

7.3.1 Logic Underlying the Developed Policy Guidelines

The overall logic can be briefly summarized under three groups of considerations: technical, information availability and administrative.

7.3.1.1 Technical

Seal coating is a surface dressing that can help restore some surface properties, but does not add to the structural strength of the pavement. Therefore, it cannot fix structural problems such as fatigue cracking. Seal coats take time to cure. Therefore, under normal procedures that do not allow for lane closure for any extended period of time, seal coats should not be subjected to high traffic (volume > 2500 AADT). If seal coats are to be applied on high volume roads, strict traffic controls are needed. Seal coats should not also be applied to areas that require intense snow plough action. Heavy trucks are not believed to cause any special problems to seal coats, rather, it is the total traffic that is significant. In order to maximize life expectancy and cost effectiveness, seal coats are better used on fair condition pavements and not on pavements which have structural deficiencies.

7.3.1.2 Information Availability

Skid Number is a surface condition indicator; hence it is a justifiable criterion for making seal coating decisions. PSR, which is a combined measure of surface distress and comfort of the ride, is indicative of surface condition as well as subbase performance. As such, poor PSR values can be the result of poor surface condition, poor subbase performance, or both. It is a justifiable criterion for making decisions as long as it is accompanied with other essential information such as the presence of rutting, pumping and so on. RN is indicative of the vertical profile of the pavement which is primarily affected by the subbase performance, although it sometimes can be affected by the surface condition of the pavement (such as wide cracks, thermal curling of slabs, and so on). In most severe roughness cases, seal coating cannot solve the problem. Age of the pavement is another useful indicator of the expected pavement condition. However, it should be recognized that poor surface conditions can develop at an early age and old pavements may still be in good condition. Hence, only age as a criterion may not be a good indicator.

7.3.1.3 Administrative

Administrative considerations include the priority of the road in terms of its usage level and the availability of funds. To illustrate the role of these two factors, if the road is in poor condition, relatively in high usage (volume > 1000 AADT) and capital funds are not a problem, higher order activities than seal coating, such as thin overlays, may be warranted. If the road is not in high use but the condition is poor and capital funds are a problem, seal coating may be the desirable solution.

7.3.2 Policy Guidelines

The policy guidelines are composed of two parts: the first part is a general statement for direction on general applicability and usage; and the second part provides a set of definitions and rules to assist in the classification of seal coating needs.

7.3.2.1 General Policy Statement

Seal coating shall be used on low or medium traffic volume roads in the amounts necessary to correct existing surface deficiencies or to prevent the development of more serious structural problems in the future. Specifically:

a. Seal coating may normally be applied on flexible or composite (asphalt overlay on PCC) pavements carrying 2500 AADT or less; it can be applied on roads carrying more than 2500 AADT provided adequate traffic controls are put in place in order to ensure sufficient time for curing;

b. Chip or sand seal coating should be considered when such roads show signs of general spread of slipperiness, oxidization, raveling, spalling, erosion (dusting) or permeable surface.

c. Seal coating may also be considered as an alternative measure to delay capital spending in the absence of adequate funds on any volume road.

7.3.2.2 Definitions of Seal Coating Needs

Roadway sections that meet the low usage and bituminous surface criteria set in the general policy statement are expected to fall into one of four seal coating priority groups, as defined below:

a. Priority Group 1

1. For safety reasons, roads (young and old) that are in good condition but have lost their skid resistance (SkidN<30), and having significant levels of usage (volume >1000 AADT);
2. Old roads that are in fair condition but showing signs of aging in terms of oxidization, mild alligator cracking, and so on;
3. Young roads with significant level of usage (volume >1000 AADT) that are experiencing problems associated with surface mix quality such as bleeding; and
4. Roads that are raveling or showing signs of erosion or permeable surface.

b. Priority Group 2

1. Low usage roads (volume<1000 AADT) that are in good condition but with poor skid resistance; and
2. High usage roads (volume>1000 AADT) experiencing only roughness problems which are caused by poor surface finish and not due to supporting structure failure.

c. Priority Group 3

1. Roads that can not be resurfaced due to shortage of capital funding and where resurfacing has been delayed at least 2 to 2.5 years; and
2. Roads that are at a low level of serviceability (PSR < 2.0) but are not scheduled for capital work in the near future.

d. Priority Group 4

1. Roads that have roughness problems only and have good PSR and no skid problems;

2. Roads that are suffering from structural problems along with surface problems; and
3. Roads with curbed sections.

7.3.2.3 Sand or Chip Seal

Following are some rules relating to when chip seals and sand seals should be applied.

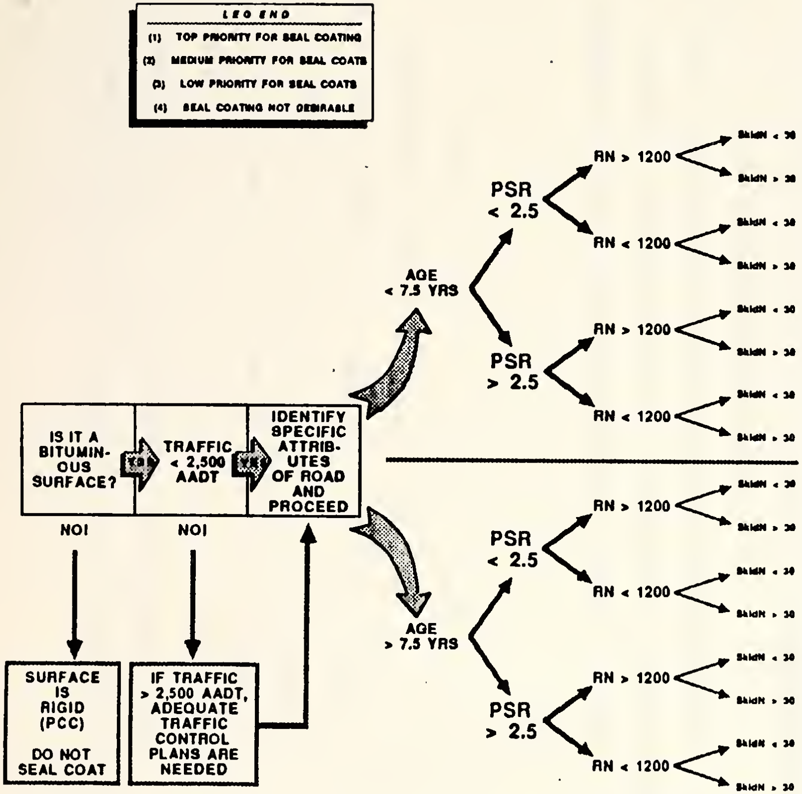
1. If the problem being addressed is oxidized pavement, then sand seals are more cost-effective for use; if the pavement is highly cracked, chip seals should be used because sand seals do not seem to effectively hold the cracked pavement together.
2. Chip seals tend to give more bleeding problems than sand seals. Hence, for bleeding pavements, sand seals would be more effective to use.
3. If the source of poor skid resistance is the loss of fine matrix around the coarse aggregates, then sand sealing would be more effective to use.
4. If the problem to be fixed is spalling, only chip seals should be used; sand seals cannot fix this problem effectively.
5. If the pavement is suffering from severe raveling or intense cracking, chip seals should be given priority over sand seals.
6. In the case of double sealing, sand seals could be considered as an option for the first seal coat application.
7. The final choice of sand or chip seal would have to take into consideration the availability of quality materials. For example, good sand seals can give better friction than poor chip seals.

7.3.3 Criteria for Specific Project Decisions

The decision tree presented in Figure 7.2 is to be used as a guide for the interpretation of the policy in management decisions relating to seal coating activities. The tree was built around four readily available items of information within INDOT: Skid Numbers, Pavement Serviceability Ratings, Pavement Age, and Roughness Numbers. Skid Numbers, Roughness Numbers and Pavement Age (calculated from the last year of construction or resurfacing) are available from INDOT Research Division, and information on PSR is included in the Road Life Records maintained by the Program Development Division. Following the appropriate path using the available information on these four items for the case under consideration leads to a recommended technical solution and programming priority under financial constraints.

To illustrate, consider a 7 year old flexible pavement section with 2000 AADT, that has mild surface alligator cracking with PSR of 3.0, skid number of 25, and RN of 1200. Using the decision tree, the surface is bituminous, traffic is less than 2500 AADT; normal procedure applies. The pavement age is in the less than 7.5 years group which is the upper half of the decision tree. Since PSR greater than 2.5 and roughness of 1200 and skid number less than 30, surface related problems most likely exist. Under such conditions, seal coating is the preferred strategy. In this case, the roughness number is on the dividing line and judgement of the user is needed because these measurements can vary by up to 10-15%, as discussed earlier in this document. In this example, the same desirable solution is reached when following either decision choice branch.

With no financial constraints, the technical solution would be implemented. In reality, however, administrative criteria tend to affect the ultimate decision, particularily under tight budgets. The two most significant



PROBABLE AREA OF PROBLEM	PREFERRED STRATEGY FROM TECHNICAL VIEWPOINT: *FUNDS ARE NO PROBLEM*	RECOMMENDATION WHEN *CAPITAL IS A PROBLEM*	
		RELATIVELY HIGH USAGE (TRAFFIC > 1000 AADT)	RELATIVELY LOW USAGE (TRAFFIC < 1000 AADT)
SURFACE, SUBBASE AND/OR SUBGRADE	REHABILITATE	(4)	(4)
SUBBASE AND/OR SUBGRADE	REHABILITATE	(4)	(4)
SURFACE	SEAL COAT	(1)	(1)
SURFACE	SEAL COAT	(1)	(2)
SURFACE	SEAL COAT	(3)	(3)
SURFACE	SEAL COAT	(2)	(3)
SURFACE	SEAL COAT	(1)	(1)
NORMAL WEAR	ROUTINE MAINTENANCE	(4)	(4)
SURFACE, SUBBASE AND/OR SUBGRADE	REHABILITATE OR RECONSTRUCT	(4)	(4)
SUBBASE AND/OR SUBGRADE	REHABILITATE	(4)	(4)
SURFACE	RESURFACE OR SEAL COAT	(1)	(3)
SURFACE	RESURFACE OR SEAL COAT	(1)	(2)
SURFACE	RESURFACE	(3)	(3)
SURFACE	SEAL COAT	(2)	(3)
SURFACE	SEAL COAT	(2)	(3)
NORMAL WEAR	ROUTINE MAINTENANCE	(4)	(4)

Figure 7.2

Criteria for Specific Project Decisions: Chip and Sand Seal Coating administrative criteria are the level of usage of the road and the availability of capital. To illustrate such influences, consider the case where the road section in the upper example was 9 years old. The desirable solution would then change. For that combination of conditions and considering the 1200 roughness number on the serious side due to the mild alligator cracking, the decision path would be for that of RN> 1200. In these circumstances, surface related problems are probably prevailing and resurfacing is the desired solution. Now assume the funds were tight. Since the road is in relatively high use (AADT>1000), it would fall in priority grouping 3 with respect to seal coating. This group includes sections where seal coating would be a good idea to consider but not necessarily essential. The decision tree recognizes such influences and recommends both a technical and an administratively influenced solutions.

Since seal coating is a surface dressing applied to correct surface distresses, INDOT needs to collect more detailed information on such distress. When such information is available, the decision tree ought to be revised. In the meantime, however, the existing indicators can be used to make decisions.

CHAPTER 8

LONG TERM MONITORING OF ROUTINE MAINTENANCE ACTIVITIES

While carrying out the statistical analysis in Chapter 5, some major problems with the available historical data were experienced. Contrary to the intuitive expectation and from the engineering point of view, some maintenance activities indicated no significant impact on RN and/or PSR. These results can be attributed to the high level of noise in the data caused by averaging, missing values and from improperly reported maintenance quantities. Consequently, low r-squared values were obtained in the statistical analysis. The extremely low r-squared values obtained for composite pavements were indicative of combined problems of data irregularity and perhaps the absence of some essential variables such as design type of PCC and quality of drainage.

Tables 8.1 and 8.2, for example, summarize the results of statistical analyses to quantify how much impact on PSR and RN do routine maintenance activities have on rigid and composite pavements. It can be observed that except for a few cells, significance was almost totally missing. Some cells had zero observations as well. The results point to the poor control of the sample and poor quality of the data. This type of results can be attributed to the observational, rather than experimental, nature of the data used. When no controls are excercised over the combination of variable levels at the time the data are collected, the effects get confounded and become difficult to separate after the fact. The confounding problem was evidenced in the rapid increase in r-squared values when five or more factor-level interactions were included in the model. As to why higher order factor interactions are not acceptable in models lies in the fact that models containing such interactions are not operational; higher

Table 8.1

Summary of Quantifying the Relationships Between
PSR and the Pavement Section Attributes

CLIMATIC REGION	HWY CLASS	STATISTICAL INDICATORS	COMPOSITE	RIGID	
				PLAIN	JOINTED REINFORCED
NORTH	ISH	Adj. R^2	0.0000	NO OBSERVATIONS	0.6194
		(P>F)	0.4278		0.0008
		SIGNIFICANT VARIABLES	NO SIGNIFICANCE		AGE MAINTENANCE
	OSH	Adj. R^2	0.0140	0.0952	0.2162
		(P>F)	0.2205	0.2741	0.0608
		SIGNIFICANT VARIABLES	NO SIGNIFICANCE	NO SIGNIFICANCE	AGE MAINTENANCE (marginally)
SOUTH	ISH	Adj. R^2	0.1332	0.8980	0.8277
		(P>F)	0.0088	0.0001	0.0001
		SIGNIFICANT VARIABLES	AGE LOADING	AGE LOADING MAINTENANCE	AGE LOADING MAINTENANCE
	OSH	Adj. R^2	0.0205	0.1707	0.0134
		(P>F)	0.0941	0.0044	0.3394
		SIGNIFICANT VARIABLES	NO SIGNIFICANCE	AGE	NO SIGNIFICANCE

Table 8.2

Summary of Quantifying the Relationships Between
RN and the Pavement Section Attributes

CLIMATIC REGION	HWY CLASS	STATISTICAL INDICATORS	COMPOSITE	RIGID	
				PLAIN	JOINTED REINFORCED
NORTH	ISH	Adj. R^2	0.0465	NO OBSERVATIONS	0.2926
		(P>F)	0.2030		0.0036
		SIGNIFICANT VARIABLES	NO SIGNIFICANCE		MAINTENANCE
	OSH	Adj. R^2	0.1054	0.8501	0.2052
		(P>F)	0.0001	0.0001	0.0016
		SIGNIFICANT VARIABLES	AGE MAINTENANCE THICKNESS (marginally)	THICKNESS (marginally)	LOADING MAINTENANCE
SOUTH	ISH	Adj. R^2	0.1576	0.5159	0.5812
		(P>F)	0.0009	0.0001	0.0001
		SIGNIFICANT VARIABLES	MAINTENANCE	AGE LOADING	LOADING AGE (marginally)
	OSH	Adj. R^2	0.1698	0.1412	0.0267
		(P>F)	0.0001	0.0013	0.2535
		SIGNIFICANT VARIABLES	AGE LOADING	AGE	NO SIGNIFICANCE

order effects are not only difficult to interpret physically but are also difficult to quantify. Hence, interactions cannot be used as input variables into performance or cost models.

It is obvious that the observational data collected from crew day cards cannot be used to provide conclusive answers to the question of routine maintenance effectiveness. To answer the important question of "how much impact", it would be necessary to use a controlled experiment approach. This approach will not only answer the raised question, but will provide more reliable performance and cost functions for use by INDOT in the future analysis of maintenance and rehabilitation strategies. With an appropriate statistical design, only select cells need to be filled in.

The Strategic Highway Research Program (SHRP H-101) is currently undertaking a study in the area of routine maintenance effectiveness. Two seal coating types are under consideration for bitumious pavements and include slurry seal and chip seal. Undersealing and joint sealing activities are also included for rigid pavements. The SHRP study is addressing maintenance activities at the national scale and may not come up with relationships and/or recommendations which are specific to Indiana's circumstances. In fact, only generalized functions can be expected at this point in time. Indiana, therefore, may have to carry out some of its own experiments in order to operationalize SHRP's conclusions and recommendations. The recommended long term monitoring program contained in this chapter took into consideration the bridging requirements with SHRP activities.

The following sections will address the design and layout of the proposed controlled experiments, as well as other long term monitoring activities that need to be carried out.

8.1 Controlled Experiment : Design and Layout

The overall objective of this series of controlled experiments is to gather more reliable information and better quality maintenance data than what exist at present. Such data can be used to establish more precisely the role of routine maintenance in pavement management. For example, to quantify the impact of level of maintenance on pavement damage, to develop pavement performance equations given various types of maintenance treatments, and to estimate required maintenance funds as a function of surface condition.

8.1.1 Proposed Experimental Design

First, the overall concept is described; next, the various factors and their levels are defined; and finally, the experiment physical layout is described.

8.1.1.1 The Concept

The development of the profiles of both low order (or basic such as crack sealing, joint sealing, and patching) and higher order routine maintenance (such as chip and sand seal coating) activities requires detailed information on:

- how much maintenance of a given type was needed in terms of production units;
- on what type of pavement;
- when;
- at what overall pavement condition level;
- to fix what type of distress; and
- how much it costed in terms of materials, labor and equipment use.

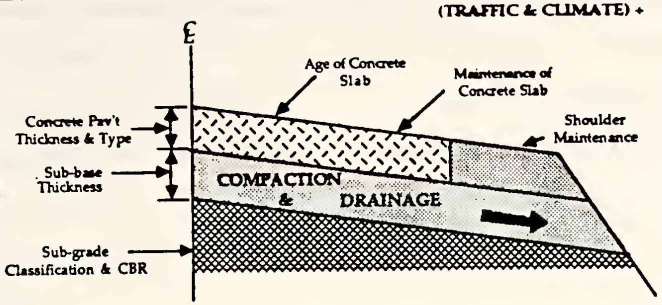
Such information needs to be collected for a life cycle, the period between a new construction or resurfacing and the next resurfacing.

In order to assist in filtering the effects of the exogenous variables, roadway sections with minimum lengths of 1.5 miles should be selected and subdivided into a number of subsections, where different types of treatments, or different levels, are applied at the same location. The effects of the site properties and pavement attributes on the effectiveness of maintenance, as well as the effects of usage, climate and pavement attributes on performance can then be filtered. In that manner, the limits to the effectiveness of maintenance can be defined.

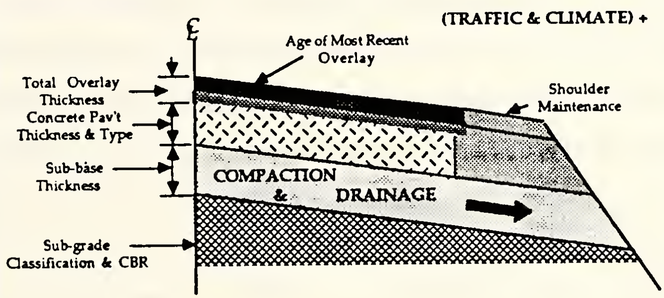
8.1.1.2 Factors Affecting Performance: Low Order Routine Maintenance

Figure 8.1 illustrates the factors that influence the performance of pavements in addition to traffic and climate. These factors and their levels can be summarized as follows:

1. FOR RIGID AND COMPOSITE PAVEMENTS
   - a. Climate : 2 (North and South)
   - b. Traffic : 2 (High and Low)
   - c. Design Type of Concrete Slab : 2 (Plain & Reinforced)
   - d. Slab Thickness : 2 (Thick and Thin)
   - e. Subbase : 2 (Dense and Stabilized)
   - f. Subgrade : 2 (Coarse and Fine)
   - g. Total Pavement Thickness : 2 (Shallow (t<9") and Deep (t>9")
2. FOR FLEXIBLE PAVEMENTS
   - a. Climate : 2 (North and South)
   - b. Traffic : 2 (High and Low)



Factors Affecting the Performance of Rigid Pavements



Factors Affecting the Performance of Composite Pavements

Figure 8.1

Factors Affecting the Performance of Pavements

c. Surface Type : 2 (Original/Resurfaced)

d. Subbase Thickness : 2 (Thick and Thin)

e. Subbase : 2 (Dense and Stabilized)

f. Subgrade : 2 (Coarse and Fine)

g. Total Pavement Thickness : 2 (Shallow and Deep)

8.1.1.3 Low Order Maintenance: Size of Experiment

The above arrangements add up to a total of 128 cells. With 1/4 replications (32 extra observations) as an error term required to create a stable statistical test, the total number of observations required for each type of pavement would be equal to 160 sections. This is a major undertaking; to make it reasonable in size, there are two options. The first option is to reduce the number of variables at the cost of developing incomplete understanding of the factors involved; and the second, to use fractional designs at the expense of confounding some of the factor effects. The latter choice is preferred because information on all key variables and their primary interactions can be obtained while confounding the effect of higher order interaction. A fractional factorial design of the type 2**(7-2) can reduce the number of observations significantly, down to about 40 sections per pavement surface type (including 1/4 replications). This is a much more reasonable number of observations to maintain and monitor very closely and in detail. In fact, the samples should be weighted to reflect the relative distribution of surface types in Indiana's total highway network.

8.1.1.4 High Order Routine Maintenance: Factor Levels

Chip and sand seal coats are generally applied to low volume roads; consequently, traffic drops as an important factor, but the following factors remain:

1. FOR COMPOSITE PAVEMENTS (Asphalt Overlay on PCC)
   a. Climate : 2 (North and South)
   b. Design Type of Slabs : 2 (Plain and Reinforced)
   c. Subgrade : 2 (Coarse and Fine)
   d. Subbase : 2 (dense and stabilized)
2. FOR FLEXIBLE PAVEMENTS
   a. Climate : 2 (North and South)
   b. Subgrade : 2 (Coarse and Fine)
   c. Subbase : 2 (dense and stabilized)

8.1.1.5 High Order Maintenance: Size of Experiment

Allowing for 1/4 replications, 20 sections of composite pavement and 10 sections of flexible pavements would be required for this experiment. In contrast to low order maintenance experiment, the numbers are reasonable in size and fractional factorial designs are not needed.

8.1.2 **Layout of Sections**

As discussed earlier, the sections for all the experiments would have a minimum overall length of about 1.5 miles in order to allow for its subdivision into smaller stretches of 1100 to 1600 feet of length, each receiving a different treatment or a different level of the same treatment. The recommended typical layout of the sections included in the sample strips are shown in Figures 8.2 and 8.3 for low order and high order maintenance, respectively. The recommendation of this layout is based on the ease of comparison of every two adjacent sections with each other by the evaluating teams.

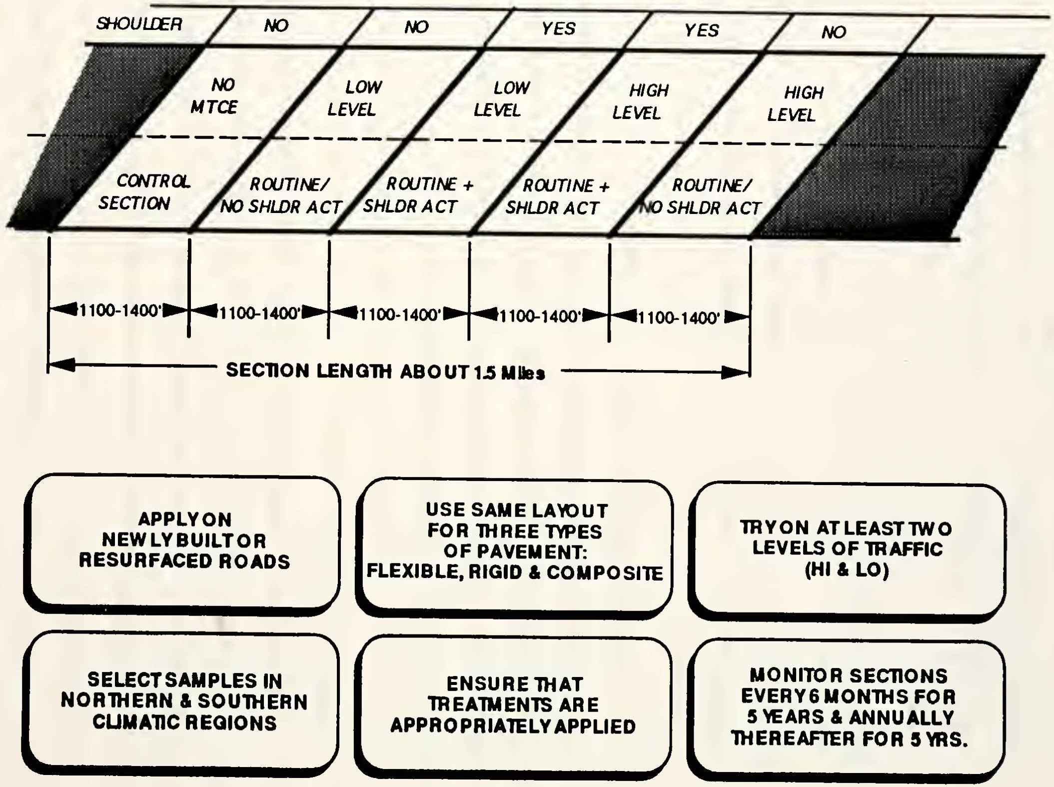


Figure 8.2

Observation Layout for Low Order Routine Maintenance Controlled Experiments.

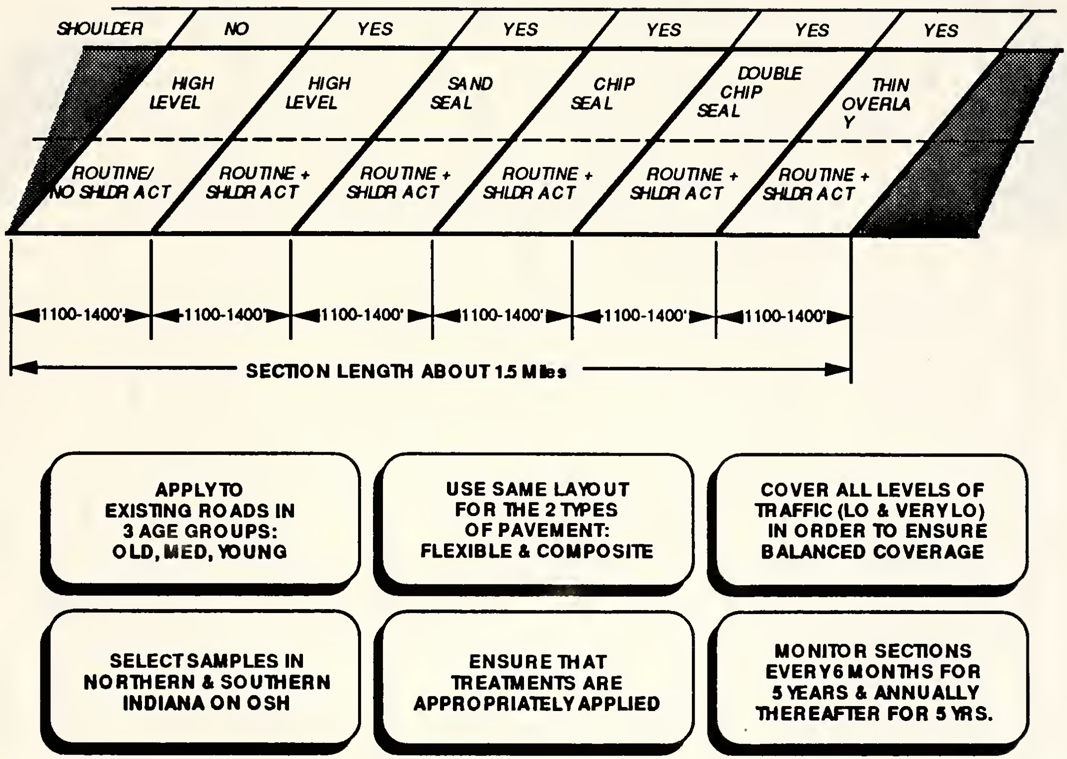


Figure 8.3

Observation Layout for Higher Order Routine Maintenance Controlled Experiments.

8.1.3 Strategies for Reducing Cost of Experimentation

The above described experiment can be further reduced by combining lower order and higher order maintenance experiments on the same sections, as shown in Figure 8.4; the idea of factorial design is still maintained. Under this combined arrangement, smaller total number of sections will be needed and more factors can be analysed for seal coating. However, the field operation and subsequent monitoring becomes more complex. Nonetheless, the overall cost will be reduced.

If the overall cost of the experimetal program, with all the above arrangements considered, is still unacceptable, then INDOT can pick a few sections that are newly surfaced and monitor very closely the maintenance activities associated with them and their performance over time. Based on the experience gained in the current study, the existing general record keeping practices have proven inadequate for evaluation purposes. Hence more accurate recording of the activities by production element and more detailed information on the condition and types of distresses are needed. A "special status" for the selected experimental sections needs to be recognized.

8.1.4 Long Term Data Monitoring

This is subdivided into three categories: before maintenance is applied; during application; and after application.

a. Before Application of Routine Maintenance

- pavement design type
- age of pavement
- subgrade: classification and CBR
- subbase : type and thickness
- quality of drainage

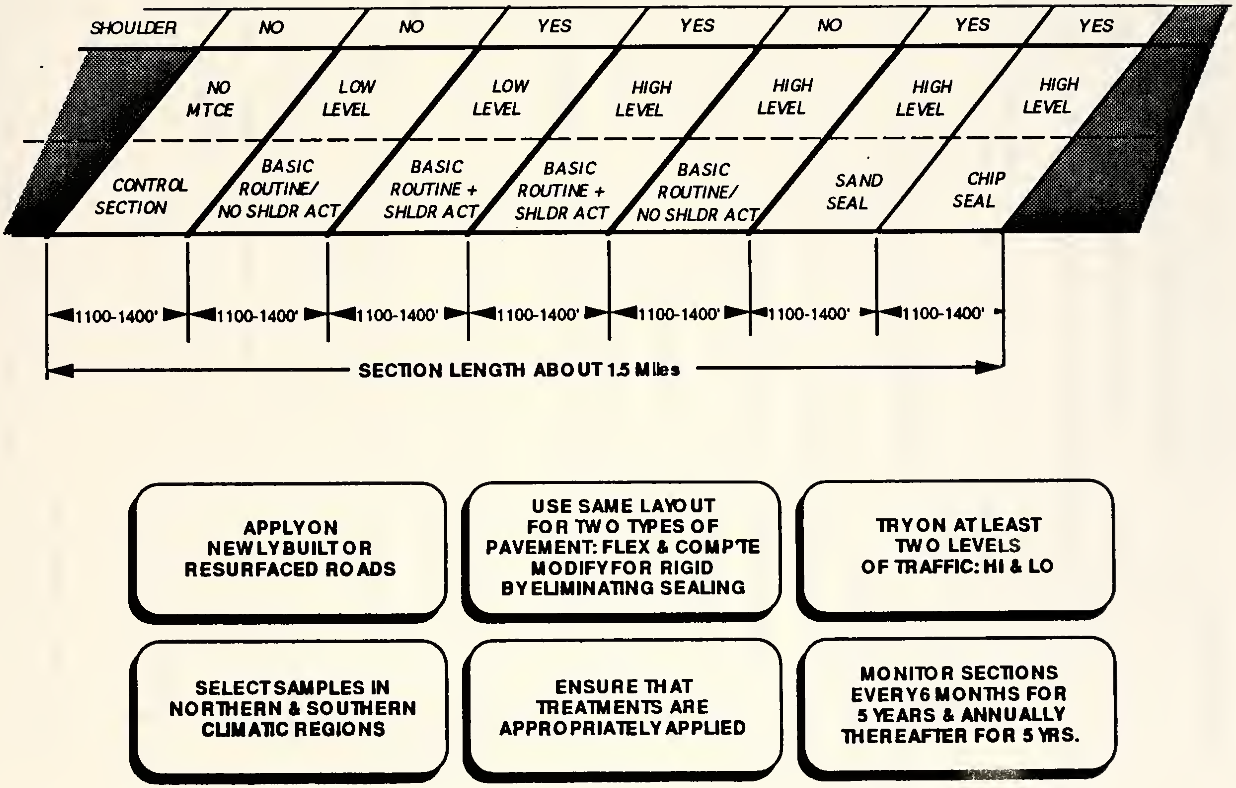


Figure 8.4

Observation Layout for a Combined Strategy of Routine Maintenance Controlled Experiments.

- thicknesses of slabs and overlays
- condition :
  - overall (RN, SkidN, PSR, Deflections);
  - by distress type (surface defects, structural failures, climatic/moisture induced distresses);
    - extent and
    - severity of distress should be recorded.
- traffic level and type.

b. During Application of Routine Maintenance

- proper records of:
  - the type of maintenance,
  - type and quantity of materials used,
  - amount of labour and
  - type and amount of equipment used,
  - the amount of production units
- weather (sunny, rainy, humid; hot, cool or cold; windy, not windy; and so on)
- special problems worthy of noting

c. After Application of Routine Maintenance

- general condition indicator measurements: RN, PSR, SkidN, Deflections (within few weeks from action).
- detailed distress survey showing types, extent and severity
- Every 6 months, for 5 years, repeat same measurements and record distress by type and/or any other special problems; annually thereafter and until the end of life cycle.

8.1.5 Experiment Management

The proposed series of experiments can be staged over time and can be re-directed whenever necessary. The experiments are better carried out within each pavement type than fractionally accross all pavement types. This tactic has three advantages: 1) data mixing problems are minimized; 2) interim evaluation can be made, which is essential for redirecting the program, or could be utilized in practice; and 3) the overall conclusions at the end of the experiment would be easier to derive.

8.2 Other Long Term Monitoring Activities

Obtaining detailed data on a select sample of the highway network is useful for generating the performance and cost functions discussed earlier. In order to establish the role of routine maintenance in pavement management, the above data need to be supplemented with a number of statewide aggregate pieces of information, including:

a. the amount of overall maintenance spending per year (by activity type, if possible) and its relationship with the network's average age and condition;

b. the relationship of overall maintenance spending with capital spending; and

c. the relative level of productivity of various routine maintenance activities (by district).

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

The evaluation of any given activity can be either summative or formative. In the summative approach, the evaluation seeks to produce a conclusive statement on the performance of the activity under study or its progress towards the achievement of its intended goals and objectives. In the formative approach, the focus of the evaluation shifts towards the development of some guidelines and recommendations that could be used to redirect that activity in order to enhance its overall performance. The present study was a mixture of both approaches. It addresses three main concerns or issues as mentioned below:

1. Do routine maintenance activities make a difference in the pavement's serviceability or service life? If yes, how much?
2. Is chip and sand seal coating cost-effective in comparison to other alternatives? When is the optimal timing for seal coating?
3. What policy framework and management criteria should INDOT use in the guiding and management of its seal coating activities?

The two questions as to whether maintenance makes any difference and whether it is cost-effective are summative in nature; finding the optimal timing for seal coating and the development of policy guidelines for managing it are formative.

9.1 Evaluation of Routine Maintenance Effectiveness

In answering the question whether routine maintenance activities make a difference in terms of pavement serviceability and/or service life, a statistical method was used by employing the "before/after comparison" of the means of groups of pavements that received maintenance of a given type and those pavements that received zero maintenance. The significance of the comparisons was evaluated using two indicators: r-squared (the portion of variance in the dependent variable that could be accounted for), and the F-value (a measure of the signal to noise ratio in the data). Tables 9.1 and 9.2 summarize the significant findings of the tests described in Chapter 5. The presented groupings were based on the criteria displayed in Table 9.3.

1. Since the data were found to contain a high level of noise, and since other factors which are important for the complete understanding of pavement performance were not available, (e.g., drainage, subbase and subgrade types), a relatively low value for r-squared (25%) was considered as significant. To illustrate, the test was considered as "definitely significant" if its r-squared value exceeded 25% and the probability of obtaining an F-value in a repeat experiment that is equal or greater than the one obtained in this test (P>F) was equal or less than 0.05 (or 5%). If, however, the (P>F) was greater than 0.05 but less than 0.10, the test was considered "marginally significant".
2. A specific variable within a given test was considered as "definitely significant" if its (P>F) was less than or equal to 0.05, and "marginally significant", if its (P>F) was greater than 0.05 but less than 0.10.
3. If the test explained a portion of the variance which was less than 25% of the variance (r-squared less than 0.25), the test was considered as "marginally significant even its (P>F) value and that of the specific variable under consideration were found to be equal to 0.05 or less. If either (P>F) was found greater than 0.05 but less than 0.10, the test was considered as "not significant".
4. All other combinations that are not mentioned in the above criteria were

Table 9.1

Summary of Findings of the Statistical Testing of Activity Effectiveness for Rigid and Composite Pavements

	RIGID		COMPOSITE	
	RN	PSR	RN	PSR
DEFINITELY SIGNIFICANT	PATCH* CLASS* LOCATN [CRACK SL + SHLDR ACT.]	PATCH PATCH* DESIGN TYPE PATCH* CLASS* LOCATN CRACK SL SHLDR ACTIV. [PATCH + CRACK SL] [PATCH + SHLDR ACT.]* DESIGN TYPE [CRACK SL + SHLDR ACTIV] [PATCH + CRACK SL]* CLASS*LOCAT ALL ACTIV* LOADING	CRACK SL* AGE SHLDR ACTIV SHLDR ACTIV* CLASS SHLDR ACTIV* LOADING SHLDR ACTIV* THICKNESS [PATCH + CRACK SL] [PATCH + CRACK SL]* AGE ALL ACTIV* LOADING	—
MARGINALLY SIGNIFICANT	[PATCH + CRACK SL]* LOCATN [PATCH + JOINT SL]	PATCH * LOCATN	PATCH * CLASS* LOCATN [PATCH + SEAL COAT + SHLDR ACT]* AGE ALL ACTIV	—

Table 9.2

Summary of Findings of the Statistical Testing of Activity Effectiveness for Flexible Pavements

	FLEXIBLE			
	OSH		ISH	
	RN	PSR	RN	PSR
DEFINITELY SIGNIFICANT	BRM	—	—	—
	BRM*AGE			
	[BRM + C.S.]* DIST			
	[BRM + C.S.]* AGE			
	[BRM + S.S.]			
	[BRM + S.S.]* AGE			
	SHLDR ACTIV			
	SHLDR ACTIV* DIST*AGE			
	SHLDR ACTIV* DIST*TRAF			
	SHLDR ACTIV* AGE*TRAF			
	[BRM + C.S. + SHLDR ACTIV]* DIST			
	[BRM + C.S. + SHLDR ACTIV]* AGE			
	[BRM + S.S. + SHLDR ACTIV]* DIST			
MARGINALLY SIGNIFICANT	BRM*DIST	BRM*DIST	BRM	—
	[BRM + S.S.]* DIST	[BRM + C.S.]* AGE	BRM*DIST	
	[BRM + P.LEVL]* AGE	[BRM + S.S.]* AGE		
	[BRM + P.LEVL]* DIST	[BRM + SHLDR ACTIV]*DIST		
	[BRM + SHLDR ACTIV]*AGE	[BRM + SHLDR ACTIV]*AGE		
	[BRM + SHLDR ACTIV]*DIST* AGE	[BRM + S.S. + SHLDR ACTIV]		
	[BRM + P.LEVL+ SHLDR ACTIV]* DIST	[BRM + S.S. + SHLDR ACTIV]* AGE		

Table 9.3

Criteria for Statistical Significance Classification

		TEST			
		R^2 >= 0.25		R^2 < 0.25	
		(P>F) <= 0.05	(P>F) > 0.05	(P>F) <= 0.05	(P>F) > 0.05
VARIAB LE	(P>F) <= 0.05	DEFINITELY Significant	MARGINALLY Significant	MARGINALLY Significant	NOT Significant
	0.10 > (P>F) > 0.05	MARGINALLY Significant	NOT Significant	NOT Significant	NOT Significant

classified as "not significant".

Table 9.1 illustrates two phenomena: first, with respect to roughness, maintenance activities (particularily patching, crack sealing and shoulder activities) seem to display greater impact on composite pavements than over rigid; and second, with respect to pavement serviceability ratings, the same maintenance activities seem to display greater impact on rigid pavements than on composite. The major findings in this concern were summarized below by pavement type:

9.1.1 Rigid Pavement Maintenance Activity Evaluation Results

Following are the main findings on the various routine maintenance groupings; only those that displayed some form of significance in their impacts on serviceability or roughness are mentioned.

1. Patching Only -- This activity had a definitely significant impact on PSR, with such significance varying with class, location and design type. As for roughness, patching was definitely significant only for some class and location combinations.
2. Crack Sealing Only -- Crack Sealing displayed a definitely significant impact on PSR measurements. This impact was consistently strong across all classes, locations, design types and loading conditions.
3. Shoulder Activities Only -- These activities demonstrated a definitely significant impact on PSR measurements. Again this impact was consistently strong among all classes, locations, design types and loadings.
4. Patch and Crack Sealing Combined -- This group of activities had significant impact on PSR measurements, with such impact varying with class and location. It had only marginal impact on RN measurements.

5. Patching and Joint Sealing Combined -- This group had only marginally significant impact on the RN measurements.
6. Patching and Shoulder Activities Combined -- This combination demonstrated definitely significant impact on PSR measurements with such significance varying with the design type (plain or jointed reinforced).
7. Crack Sealing and Shoulder Activities Combined -- This group had a definitely significant impact on both of RN and PSR measurements. Again this impact was consistently strong across all layers of the data.
8. All Activities Combined -- This group had a significant impact on the PSR measurements, but the impact varied by the cumulative loading of the pavement.

9.1.2 Composite Pavement Maintenance Activity Evaluation Results

All the various combinations of routine maintenance activities did not show any kind of significant impact (whether definite or marginal) on PSR measurements. Significant impacts were found only on RN measurements. Following are the major findings on the various routine maintenance groupings:

1. Patching Only -- This activity showed only marginally significant impact on RN measurements and even that varied by class and location.
2. Crack Sealing Only -- Crack sealing had, for certain age groups, a definitely significant impact on RN measurements.
3. Shoulder Activities Only -- These had a definitely significant impact on RN measurements, with such significance varying with class, thickness or cumulative loading.
4. Patching and Crack Sealing Combined -- This activity group had a definitely significant impact on roughness measurements, with such

significance varying with the age of the pavement.

5. Patching, Seal Coating and Shoulder Activities Combined -- This group had only a marginally significant impact on roughness measurements, and that significance was dependent on what age group the pavement fell into.

6. All Activities Combined -- This group demonstrated a definitely significant impact on roughness measurements but only in certain locations. Across the state as a whole, it only had a marginally significant impact.

9.1.3 Flexible Pavement Maintenance Activity Evaluation Results

Evaluation was carried out for OSH and ISH separately, using the flexible pavement maintenance activity groupings the tests generally produced very low R-squared values for ISH data. Hence, most of the significant findings related to OSH attributes (roughness and serviceability), with roughness yielding more results, as illustrated below.

1. Basic Routine Maintenance - This activity had a significant impact on RN of OSH and such strength varied by Age Group; a marginal impact on RN of ISH and such marginality was dependent on which district was chosen; and a marginal impact on PSR on OSH which was variable by district.

2. Shoulder Activities - This maintenance activity had a significant impact on RN on OSH with such strength varying by Age, District and Traffic Level.

3. Basic Routine Maintenance and Chip Sealing - Significant impact for this activity grouping on RN on OSH for some Districts and Age groupings were detected.

4. Basic Routine Maintenance and Sand Sealing - This group of activities had

a significant impact on RN on OSH with strength varying by age and a marginal impact on PSR on OSH, which varied by age as well.

5. Basic Routine Maintenance and Premix Leveling - This activity showed marginal significance on RN on OSH for certain age groups and districts.
6. Basic Routine Maintenance and Shoulder Activities - This activity grouping had a marginal impact on RN on OSH for certain age groups and districts and marginal impact on PSR on OSH, where such impact varied by district only.
7. Basic Routine Maintenance and Chip Sealing and Shoulder Activities - This group had a significant impact on RN on OSH for some districts and age groups.
8. Basic Routine Maintenance and Sand Sealing and Shoulder Activities - This group had a significant impact on RN on OSH for some districts and a marginal impact on PSR on OSH, which varied by age groups.
9. Basic Routine Maintenance and Premix Leveling and Shoulder Activites - This group had a marginal impact on RN on OSH for some districts.

9.1.4 Quantification of the Impacts

Attempts to quantify the relationships between roughness or pavement serviceability, on the one hand, and the attributes of the pavement sections (age, thickness, class, etc.) did not prove to be very successful across the various pavement types, classes, design types or climatic regions. Hence, quantifications for stratified segments of the data were attempted and acceptable relationships were possible to extract. For example, equations relating to PSR and RN to flexible pavement attributes were successfully developed but similar relationships were possible only for the group of rigid interstate highways for

PSR and RN as dependent variables and for one case of rigid other state highways for RN. The significance of the variables tended to change from one stratification to the other. The poor r-squared values and the frequent change in the significant variables to be included are signs of poor quality of data.

9.1.5 Limitations of The Evaluation

The evaluation conducted in the study provided quantitative evidence of some of the positive impacts of routine maintenance activities on pavement performance. These results, however, need to be kept in proper perspective. A number of limitations that are inherent in the approach combined with problems of data quality to affect the extent to which the conclusions can be used in practice.

9.1.5.1 Limitations of the Approach

There are five limitations in this study. These are discussed separately below.

a. Due to the lack of experimental data, observational data had to be utilized in the study. These data were extracted from crew day cards, roughness measurements, pavement serviceability ratings, and other information recorded in the past. As there was no control over any of these data during their collection, the statistical analyses suffered from what is known as confounding of effects (inseperable combined effects of two or more variables). This situation compelled the study to accept a high noise level. Consequently, relatively low levels of r-squared values (as low as 25%) had to be used for significance.

b. The effectiveness of a given maintenance activity depends on the type of distress. For example, crack sealing could be very effective in treating shrinkage cracks but ineffective in treating fatigue cracking. It is important, therefore, to know whether the pavement is suffering from shrinkage or fatigue cracking when the crack sealing was applied. Analysis of effectiveness of activities by type of distress would hence be more productive in terms of defining when and where that activity should be used. INDOT does not have detailed distress information on the various highway sections but measures aggregate indicators such as RN and PSR. The study was limited by the available information. Aggregate indicators indicate symptoms of a problem, not the problem itself. The averaging of effects was thus an important source of noise in the data.

c. Because of the nature of the data, a relatively large number of variables had to be included in the analysis in order to obtain an acceptable level of significance. However, the large number of variables (8 independent variables, each with 2 or more levels) also increased the number of cells in the experiment to a large number whereby filling them all became difficult with the available observational data.

d. Rigid and composite pavements tend to have relatively long lives and consequently their average age is high. At older age, most pavements tend to receive some form of maintenance. Very few sections, therefore, met the "zero maintenance" criterion. When these few records were distributed among the so many cells in the study, the observations were inadequate in number to allow for complete testing of all situations.

e. The available data were for three years only. The "zero-maintenance" group contained those sections that did not receive any maintenance during the study period (1984-1987). It was not known whether any of these sections received routine maintenance in the years before the study period or whether the sections were scheduled for any work in the years to follow.

9.1.5.2 Data Quality Problems

This group includes four problem areas:

a. Incorrect recording of location of maintenance caused many sections to be taken as so called "zero-maintenance" sections. However, these sections were observed to gain in the order of 150 to 800 points in roughness, and 0.5 to 1.5 points in pavement serviceability rating. Since improvements in pavement condition without any action is not expected, it was assumed that the maintenance records were erroneous.

b. Some of the data were poorly co-ordinated. For example, some 22 sections in the study's random sample received seal coating (chip or sand); however, none of these sections had a complete "before and after" skid resistance measurements. The source of this problem is that seal coating is applied only on low volume roads with bituminous surfaces; these roads tend to be on other state highways, not interstates. The skid resistance measurement program, however, covers only interstates on an annual basis; other state highways, at best, get measured once in three years and sometimes more if some capital work was going on at the scheduled time of measurement. To obtain skid measurements for seal coated sections requires coordination between the maintenance personnel and the Research Division that collects skid resistance data. The lack of such co-ordination eroded the opportunity for testing the effectiveness of seal coating activities with respect to skid resistance improvements.

c. Some of the necessary information were either unknown or incomplete. For example, in many cases, the design type of the slabs under composite pavements (plain or jointed reinforced) was not known. Another example related to the quality of drainage of the pavement structure which is an important factor influencing pavement performance. However, reliable information on this variable was not readily available. Consequently, these factors were excluded from the data base causing poor results for the effectiveness analysis.

d. The data base included information from various sources with different data recording practices. Analysis of the surface change reports revealed that data were being reported by the districts on a varying basis. For example, some recorded application rates by linear miles and others, by lane miles; some kept records of the application rates and others did not. This non-uniformity of practice can produce significant amount of noise in the reported data.

9.2 Evaluating Cost-Effectiveness of Seal Coating

Cost-effectiveness evaluation for seal coating activities was based on the least life cycle cost calculated in perpetuity. The components of the life cycle cost included: the annual maintenance costs, seal coating costs, future cost of resurfacing and rehabilitation, and user costs. Major conclusions of this analysis includes:

a. Seal coating tends to delay capital spending thus giving the agency some flexibility in programming; it also saves the agency some money since agency cost tends to decrease with increase in the frequency of seal coating.

b. User costs with no seal coating are generally higher than with seal coating. As the number of seal coats increases, user costs tend to increase.

c. For sections with AADT greater than 1000, the total cost (agency cost plus user cost) decreases after the application of one seal coat, but tends to continuously increase as the number of seal coats are increased.

d. For sections with AADT less than 1000, the total cost decreases with more applications of seal coats. Hence, for these roads, multi-seal coating is cost-effective.

e. Optimal timing for sections with AADT>1000 is at PSI of 3.0 whereas that for sections with AADT<1000 is at 2.70.

f. The cost-effectiveness of sand and chip sealing is dependent on the availability and cost of good aggregates.

9.3 Developing Seal Coating Policy Guidelines

Most state agencies leave seal coating decisions in hands of district maintenance engineers and do not have written guidelines. Many of these agencies, however, indicated a need to have a uniform policy for seal coating applicable throughout an agency.

Seal coating is very much related to surface distress like raveling, erosion, skid resistance loss, and development of permeable surface. Hence the ideal criteria are expected to be in terms of measures of the extent and severity of these problems. However, INDOT does not have this type of information readily available on a routine basis; instead, they have four aggregate indicators of the pavement condition. These indicators are routinely provided to the districts and hence are very attractive as a starting point for seal coating decisions. A decision tree approach was developed in the present study based on these four basic indicators and other related factors. The tree may be revised when more detailed condition data are procured by INDOT. The following major guidelines were recommended:

1. Seal coating should normally be applied on roads with bituminous surface (flexible or composite) carrying low volumes of traffic (vol < 2500 AADT).
2. Seal coating should be used when the pavement shows signs of raveling, erosion, development of permeable surface, and/or loss of skid resistance.
3. Seal coating may also be used as a stop-gap measure to delay capital spending on any volume road.
4. The need for seal coating was classified into four priority groups with Group (1) reflecting ideal conditions for seal coating and Group (4), conditions where seal coating is a waste of time and money.
5. The use of sand seals was recommended on mildly distressed surfaces and on raveled roads where the fine matrix has been lost. Sand seals could also be considered as a first application in a double seal coating strategy but should not be used on spalled surfaces.
6. Chip seals form thicker blankets on the pavement than sand seals; as such they would be superior to sand seals in the treatment of intensive

distresses. Chip seals may not be necessarily the most cost-effective in treating bleeding pavements, mildly distressed areas, or simply oxidized pavements.

9.4 Recommendations for Future Direction

Despite the many impediments to a fuller understanding of the effectiveness of routine maintenance activities, some strides towards obtaining quantitative evidence of the impacts of these activities were made. The strong signals received through the noisy data were, beyond any doubt, significant in their indications.

Field data analysis was augmented by two other efforts: an expert opinion survey and the use of surface change reports. A number of interesting facts came about in these two efforts and are worth of mention:

a. The Expert Opinion Survey revealed that the INDOT staff surveyed had conflicting ideas about what should be the specific objectives of routine maintenance.

b. The survey also demonstrated that decision makers in Central Office and the Districts had different understanding of the pavement deterioration process and different expectation regarding various maintenance activities.

c. The Surface Change Reports demonstrated that the various districts had different preferences for different treatments, and that different materials and practices were observed to exist.

d. Some districts kept better records of what they did than others. In addition, the outputs in surface change reports were not recorded with the same units.

The above facts offer an explanation to a number of impediments that interfered with a full evaluation of routine maintenance effectiveness in this study. Evaluation, however, is a continuous process that supplies management with information -- an essential element for them to determine if the activities are going in the right direction or if it needs to be redirected. The quality of that generated information is highly dependent on the quality of the raw data used as input into the evaluation process. In order to be able to answer the questions that affect the routine maintenance evaluation process, a number of efforts can be made in the future as indicated below:

1. Improving the quality of pavement condition data that are collected on a continuous basis (SkidN, RN, PSR);
2. Improving the communication and coordination among the various units in charge of routine maintenance.
3. Setting up a series of controlled experiments where maintenance records are kept in detail along with associated factors thus allowing for better filtered data.

9.4.1 Recommendations on Improving the Quality of Data

The existing data sources within INDOT, as demonstrated in this study, contain a high degree of noise. In order to reduce the level of noise in the data in the future, the following specific actions are recommended:

1. Measurements of RN, PSR, SkidN, and deflections should be done according to statistical sampling principles so that the representability of these measurements can be based on more than one measurement per section, as it is done at present.
2. A specific group within INDOT should be made responsible for

making sure that maintenance reports from various districts are uniformly recorded and certain measures of quality assurance are followed.

3. A common geographic referencing system should be followed for all INDOT data files thus reducing the guess work involved in determining maintenance quantities to the roadway sections -- a main source of error in the manipulated data.
4. It may be desirable to include surface related distress measurements into the INDOT pavement evaluation process.

9.4.2 Improving Internal Communication and Co-ordination

In order to overcome the problems related to data uniformity and consistency in maintenance decision-making, improvements in the internal communication of the maintenance program units may be sought. Following are some recommendations that may be considered:

1. Operations Support Division should investigate the best method for coordinating the data gathering efforts with the Roadway Management Group, Research Division, and District Maintenance Engineers.
2. It may be necessary to assign a maintenance management staff the task to ensure that appropriate field measurements are being taken and to interact with the district maintenance personnel.
3. Periodic workshops should be organized for both central office and district maintenance personnel to create common understanding of the basic objectives, options, considerations and

priorities in the routine maintenance area.

4. It is necessary to formalize the production of some key documents involving pavement performance. Suggested ideas would include:

   a. the production of a summary report of the highway system's characteristics, age and condition as a means for checking on the quality of information on an annual basis. The existing reports do not indicate pavement condition data by pavement design type (flexible, rigid and composite) nor do the reports mention how many miles of interstate and other state highways each district has with flexible, rigid and composite surfaces. The understanding is that the current data structure does not allow for extracting this type of information; hence modifications to the process or enhancements in the automation of the existing system may be essential.

   b. the preparation of a trends document relating the changes in essential management decision variables affecting pavement capital and maintenance, on a state and district levels. Such trends may portray pavement conditions; maintenance and capital spending; climatic factors (snow fall, temperature); manpower employed by the various spending areas; and so on.

9.4.3 Undertaking a Series of Controlled Experiments

A long term monitoring of maintenance activities was recommended in the study. Without this type of monitoring, stable and reliable relationships can not be developed for their meaningful use in making pavement maintenance management decisions.

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